Proposal of a Hybrid Algorithm for Burst Transmission in Wireless Sensor Networks

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Declaration

I hereby affirm that I composed the present work independently and all the sources, tools and quotes that are directly or indirectly taken over from other sources are marked as such. I confirm that I acknowledge the applicable doctorate regulations of the Faculty of Computer Science of the Technical University Dresden.

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Abstract

The remarkable growth in the applications of low power wireless networks (LPWNs) in various disciplines such as health-care, wildlife monitoring, unmanned vehicles and the emerging Internet of Things (IoT) brings along various challenges. Such applications demand the transfer of large amounts of data in short durations. Unlike conventional medium access control protocols, which force each competing node to contend for each packet it transmits, bulk data transmission enables a node to exclusively use a channel for transferring a large amount of data in succession. Bulk data transmission is a technique in which a sender node is granted exclusive access of the channel in order to transmit all the packets accumulated in its buffer. However, there are two problems with this strategy: (1) For how long should bulk data transfer last if there are multiple contending nodes? (2) How should this strategy deal with the significant fluctuation in the quality of a low-power wireless link? Understanding link quality fluctuations in a wireless sensor network is useful for various reasons. For example, nodes can determine when and for how long they should transmit packets, so that they can reduce the packet loss rate and the cost of retransmission (delay as well as power consumption). However, the quality of a link depends on many factors, which cannot be known except in a probabilistic sense.

In this dissertation, I propose an efficient burst transmission scheme that measures and models the dynamic link quality fluctuations. Introducing a large empirical study at the beginning of this dissertation leads to a good understanding of the effect of external factors such as the environment (indoor,outdoor), Cross Technology Interference (CTI) and mobility of a sender node causing link quality to fluctuate. The analysis and observations of the empirical study establishes the basis on which the model for link quality estimation is built and designed. Here I propose three approaches to deal with different aspects of link quality fluctuation.

(i) Offline approach- long-term characteristics: The offline approach models the link quality fluctuations by taking into account a large set of data. To obtain such a data set, experiments were performed on the site under study for several weeks. It was observed that the link quality fluctuates considerably even in static deployment. Understanding the stable durations, good and bad alike contribute to the efficient transmission of packets. I propose two offline approaches: (i) The first uses the conditional probability distribution function of signal-to-noise (SNR) fluctuation to estimate the expected reliable and unreliable period. (ii) The second uses k-mean clustering to characterise the link quality fluctuations into different

states where the relationship between the states is defined by transitional probabilities. The advantages of employing an offline approach is (i) availability of sufficient memory, (ii) low computational cost, and (iii) possible use of a complex algorithm. However, these approaches can not deal with short-term link quality fluctuation.

(ii) Online approach- short-term characteristics: Unlike the offline approaches, an online approach models the link quality in real time and deals with short-term link quality fluctuation. However, this approach has some limitations, such as (i) limited memory space to store data, (ii) high computational cost, (iii) and employment of a simple algorithm to estimate the burst size. My proposed online approach uses adaptive history array to estimate the duration of good and bad states from the statistics of incoming acknowledgement packets.

(iii) Hybrid approach- long-to-short-term characteristics: A hybrid approach combines both offline and online methods. I also take advantage of both offline and online models in my proposed hybrid approach. My aim is to characterise the long-term link quality fluctuation with statistics that are obtained offline and to employ the statistics of received acknowledgement packets in real-time to deal with short-term link quality fluctuations. The online statistics are used to fine-tune and calibrate the offline model.

To evaluate the performance of my proposed approaches, I implement them in TinyOS and deploy them on TelosB sensor nodes. Furthermore, the proposed approaches in this thesis are compared with the state-of-the-art approaches. The thesis concludes by showing that my approaches efficiently model the link quality fluctuation and propose correct burst size to achieve high throughput, reduce transmission delay, and power consumption under different channel conditions.

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Zeeshan Ansar

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Contents

List of Publications

The following list includes publications that form the basis of this thesis. The corresponding chapters are indicated in parentheses.

1. Zeeshan Ansar and Waltenegus Dargie, **”Adaptive Burst Transmission Scheme for Wireless Sensor Networks”**, The 26th International Conference on Computer Communication and Networks (ICCCN 2017), July 31 to August 3, 2017, Vancouver, Cananda; 2017”. (Chapter 6)

2. Zeeshan Ansar, Jianjun Wen and Waltenegus Dargie, **”Efficient Online Burst Transmission Scheme for Wireless Sensor Networks”**, The 25th International Conference on Computer Communication and Networks (ICCCN 2016), August 1-4, 2016, Waikoloa, Hawaii, USA; 2016”. (Chapter 5)

3. Zeeshan Ansar, Jianjun Wen, Eyuel Debebe Ayele and Waltenegus Dargie, **”An Efficient Burst Transmission Scheme for Wireless Sensor Networks”**,in proceedings of the 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile System, MSWiM’15, pp.151-155, ACM 2015. (Chapter 4)

4. Jianjun Wen, Zeeshan Ansar and Waltenegus Dargie, **”A Link Quality Estimation Model for Energy-Efficient Wireless Sensor Networks”**, 2015 IEEE International Conference on Communications (ICC), pp.6694-6700, IEEE 2015. (Chapter 4)

The following list includes publications that I have co-authored but are not part of this dissertation.

1. Jianjun Wen, Zeeshan Ansar and Waltenegus Dargie, **”A System Architecture for Managing Complex Experiments in Wireless Sensor Networks”**,The 25th International Conference on Computer Communication and Networks (ICCCN 2016), August 1-4, 2016, Waikoloa, Hawaii, USA; 2016.

2. Jianjun Wen, Zeeshan Ansar and Waltenegus Dargie, **”MobiLab: A Testbed for Evaluating Mobility Management Protocols in WSN”**,Testbeds and Research Infrastructures for the Development of Networks and Communities: 11th International Conference, TRIDENTCOM 2016, Hangzhou, China, June 14-15, 2016.

3. Eyuel Debebe Ayele, Jianjun Wen, Zeeshan Ansar and Waltenegus Dargie, **”Adaptive Sleep-Time Management Model for WSNs”**, 2015 24th International Conference on Computer Communication and Networks (ICCCN), IEEE 2015.

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List of Abbrevations

ACK	Acknowledgement Packet
ABT	Adaptive Burst Transmission
ARR	Acknowledgment Reception Ratio
ASL	Asymmetry Level
BDT	Binary Decision based Transmission
BF	Burst Forwarding
BRE	Bursty Routing Extension
CATS	Channel Aware Transmission Scheduler
C&B	Clear Channel Assessment and Random Backoff
CCA	Clear Channel Assessment
CDF	Conditinal Distribution Function
CF	Consecutive Failure
CPDF	Conditional Packet Delivery Function
CPESD	Conditional Probability Expected State Duration
CPB	Conditional Probability Based
CS	Consecutive Success
CSI	Channel State Information
CSMA/EB	Carrier Sense Multiple Access/Exponential Backoff
CSMA/IB	Carrier Sense Multiple Access/Increasing Backoff
CTI	Cross Technology Interference
CTP	Collection Tree Protocol
CTS	Clear To Send
DMB	Double Markov Based
ESD	Expected State Duration
ETX	Expected Transmission Count
EWMA	Exponentially Weighted Moving Average
FSMC	Finite State Markov Channel
H-DMB	Hybrid-Double Markov Based
H-LQE	Hardware based Link Quality Estimator
HMM	Hidden Markov Model
HS	History Size
ILD	Inter-Loss Distance
IoT	Internet of Things
IPI	Inter Packet Interval
Kbps	Kilo bits per second
KW	Kantorovich-Wasserstein
LQE	Link Quality Estimator
LQI	Link Quality Indication

LR	Linear Regression
MAC	Medium Access Control
MO	Microwave Oven
MS	Mobile Sender
MWSN	Mobile Wireless Sensor Network
PER	Packet Error Rate
PN	Packet Number
PRR	Packet Reception Ratio
PSR	Packet Success Rate
PT	Pause Time
R	Relay Node
RF	Radio Frequency
RNP	Required Number of Packet re-transmission
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTS	Request To Send
SF	Link Stability Factor
SIFS	Short Inter Frame Spacing
SGD	Stochastic Gradient Descent
S-LQE	Software based Link Quality Estimator
SNR	Signal to Noise Ratio
STLE	Short-term Link Estimator
TDMA	Time Division Multiple Access
TT	Transmission Time
WMEWMA	Window Mean with Exponentially Weighted Moving Average
WSN	Wireless Sensor Network

Chapter 1

Introduction

During the last decade low-power wireless sensor networks (WSNs) grew enormously, which opened the gates for new applications for sensor networks in the field of healthcare [MBIA10, JLB+10, AE11, VTV+15], industrialisation [CLP10, kGB11, ATCP10], car automation [SCKA11, YPR12, KDBB15], agriculture [DPM+11, QZX+11, QXF+14], smart cities [VGS+13, ZBC+14, VA15], water purification [.Z12, NAKB13, HHM+13] and livestock monitoring [HMY+10, NJBVC12, KP15]. These applications generate bulk data and demand high throughput to transfer data due to storage limitations in sensor nodes; hence high throughput has been achieved by enabling bulk/burst data transmission in WSN.

Burst transmission in wireless sensor networks is useful for several reasons: (1) Burst transmission provides high throughput by allowing a single transmitter to transmit multiple packets in burst once it has won a medium. (2) It avoids aimless contention by disabling clear channel assessment and random back-off (C&B) before transmitting each packet which reduces packet latency. (3) It allow a sender node to transmit its data quickly and go back to sleep sooner to conserve energy.

An essential question that has not been sufficiently addressed concerning burst transmission is determining the size of a burst. For optimal results, firstly burst transmission has to be bounded, therefore addressing this query is very important. Following which, contending nodes should estimate for how long a burst transmission would last, so that they can attempt to win the medium at the right time. The efficiency of burst transmission depends on how the quality of a link fluctuates. The longer the duration of transmission, the more likely the quality of a link fluctuates, meaning the probability of unsuccessfully transmitting packets becomes higher.

Hence, the cost (both delay and energy) of retransmission increases as well.

The aim of this thesis is to propose an efficient burst transmission scheme which determines the appropriate size of a burst by taking the statistics of link quality fluctuation into consideration. To the best of my knowledge my proposed method is the first which determines the correct size of the burst by determining periodicity in link quality fluctuation. I also provide a MAC layer solution to enable the co-existence of multiple transmitters during burst transmission by sharing information pertaining to link quality with neighbouring nodes which increases throughput and improves channel usage.

1.1 Burst Transmission and its Challenges

An upsurge in the use of wireless sensor networks and the emergence of the Internet of Things (IoT) demands high throughput which can been achieve by enabling burst transmission. However, the efficiency of the burst transmission schemes depends on the underlying quality of wireless link. The link quality in wireless sensor networks is highly dynamic and affected by several factors, including environment, interference, and mobility. The deterioration in link quality increases the packet loss rate and this loss is significant in burst transmission as multiple packets can be lost in succession.

Existing or proposed MAC protocols supporting bulk-data transmission do not react well to link quality fluctuation. Since nodes make repeated attempts to retransmit lost packets even when the statistics of received packets suggest that the channel is still bad or packet transmission will be deferred arbitrarily even though packet loss is an isolated and uncorrelated occurrence. Since most of the energy in wireless sensor networks is spent on data communication, efficient transmission schemes incorporating channel characteristics (statistics) are critical as they improve the reliability and lifetime of the networks. At present, the physical layer components mainly cater to link quality fluctuation, physical layer employs strategies such as dynamic rate adaptation, dynamic channel allocation, or dynamic transmission power adjustment to maintain link quality. These strategies, however, have a limited scope as they are capable of handling only short-term fluctuations. For-example, increasing transmission power does not affect the link quality fluctuation in many conditions. The same can be said about dynamic channel allocation. To the best of my knowledge, existing transceivers which comply with the

IEEE 802.15.4 standard do not support dynamic rate adaptation.

Alternatively, the MAC layer can deal with link quality fluctuation by providing efficient packet transmission schemes that have middle-to-long-term scope. One of these schemes can be burst transmission, even though it was first proposed to address a different concern, namely, achieving high throughput [SRP+07, SOFA11, CKB+14]. Instead of making nodes compete to win a channel for each packet they transmit (as is the case with IEEE 802.11 and IEEE 802.15.4 contention based medium access specifications), the goal is to enable nodes to transmit multiple packets in burst once they win a medium. This scheme disregards fairness, but experiment results suggest that the overall network throughput can be significantly increased. This same approach can be used to deal with link quality fluctuation. Since wireless sensor networks run over a long period of time, enough data can be collected about channel characteristics to be used to determine the duration of good and bad link quality.

1.2 Thesis Objectives

The highly dynamic link quality in wireless sensor networks requires a burst transmission scheme which adapts to the link changes to avoid packet losses and reduce energy consumption upon retransmission. Most existing or proposed bulk/burst transfer protocols do not take into account the underlying link quality fluctuation in IEEE 802.15.4 networks leading to waste of scarce resources in resource constrained WSNs. There are several ways to deal with link quality fluctuation such as increasing transmission power, channel hopping, synchronous transmission and link estimation/prediction. The focus of this thesis is on the methods of estimation. There are three methods to address the problem of link losses in burst transmission: (a) halt packet transmission on a single failure for a fixed period, (b) halt packet transmission on three consecutive packet losses for a variable period of time, and (c) predict the future duration of good and poor channel qualities.

To explain these three options in detail, figure 1.1 illustrates different strategies of handling link quality fluctuation with time-varying channels. Suppose the quality of a given wireless link is described as shown in the figure 1.1 (top). The threshold line is drawn to suggest that packets with a link quality metric below this threshold will not be delivered successfully. If a transmitter has this information a priori, it will stop transmitting exactly before the link quality

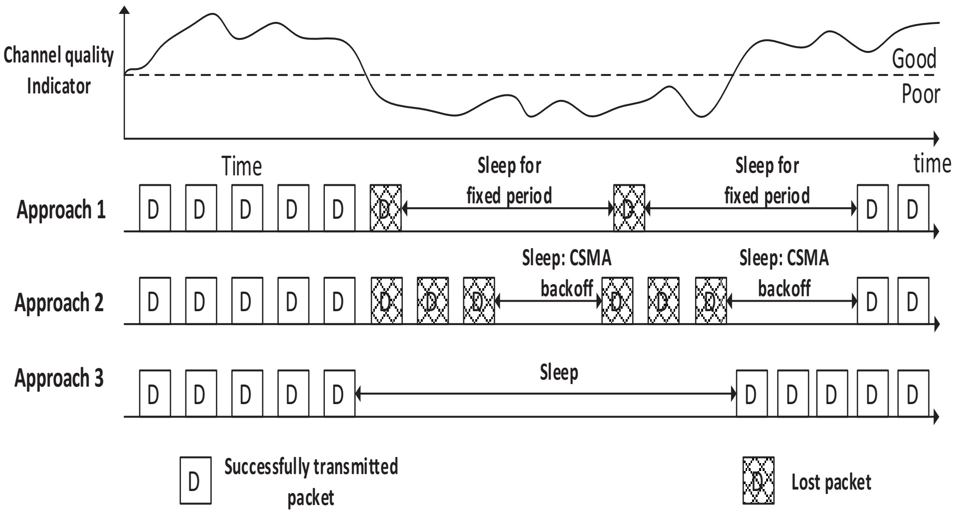


Figure 1.1: A Comparison of Different Strategies to Deal with Poor Channel Quality for Burst Transmission in Wireless Sensor Networks

falls below the threshold line. It will resume transmission when it rises above the threshold line. But this information is impossible to obtain a priori.

As the link quality falls below the threshold and a single packet drops (figure 1.1 shown in approach 1), the transmitting node halts packet transmission for a specific amount of time, then it resumes burst transmission. If, upon resuming transmission, the packet is still lost, scheme suspends transmission once again for the same duration. During suspension, the radio is turned off to save energy. The suspension period is determined empirically. The second approach, (figure 1.1 shown in approach 2), does not suspend transmission upon a single packet failure; instead, it attempts to retransmit the lost packets. If the attempt is not successful for the n-th time, the scheme performs a random back-off before attempting to resume transmission. If it still fails, it increases the back-off window exponentially and performs a random back-off once again.

A more efficient approach proposed in this thesis (figure 1.1 shown in approach 3) relies on the statistics of incoming ACK packets in order to determine the expected durations of good and bad states. In a static deployment, the link quality fluctuation statistics can be seen as stationary in a wide sense. In this case, it is sufficient to transmit a large number of packets once, establish the statistics offline, determine the expected durations of good and bad states, and use this knowledge to schedule packet transmission and sleep times. These statistics can be refreshed at runtime by evaluating the link quality metrics of received ACK packets.

This thesis also aims to model the link quality fluctuations in different environments and under different constrains (such as mobility) by estimating the correct size of a burst. Further in the thesis the outcome of sharing link quality information with neighbours on the overall throughput, end-to-end latency and power consumption of a wireless sensor network.

1.3 Thesis Contributions

In this thesis, both short and long-term link quality fluctuation are worked on by using probability estimation techniques. The investigation of link quality fluctuation begins by performing a large-scale empirical study. This study helps understand how link quality behaves under different conditions and environments. It lays the basis for my mathematical model. I continue by proposing burst transmission techniques that deal with different link quality fluctuations to improve the throughput and energy consumption. All the transmission techniques presented in this dissertation have been deployed and evaluated on real TelosB sensor nodes. The evaluations reveal high performance gain in terms of throughput, packet loss, delay and power consumption achieved by each transmission technique. The detailed results are described in the individual chapters. The specific contributions of this dissertation are highlighted below.

1. **Empirical Study of Low Power Wireless Channel (Chapter 3):** The link quality in wireless sensor networks is highly dynamic due to the inherent features of low-power wireless transceivers used by sensor nodes. The transceiver transmits a low-power signal using an on-board antenna which is highly prone to interference and multi-path fading. The limitation of the IEEE 802.15.4 radio transceiver and the highly dynamic environment in which the sensor networks are deployed affects the quality of wireless links, which in turn affects the performance of communication protocols. Link dynamics need to be taken into account when designing communication protocols. To acquire a better understanding of the problem, a comprehensive empirical study was conducted using a testbed [JZW17], designed jointly by my colleague and me, in different environments. The purpose of this study is two-fold. The first goal is to acquire a good understanding of link quality behaviour in different environments (indoor and outdoor), using static and mobile nodes, using different transmission parameters (transmit power, distance, inter packet interval (IPI) etc.) and in the presence of interference (internal and external). The second is to

investigate and find the correlation in signal strength (RSSI, SNR, LQI) and packet loss (ARR, PRR) using the available and extensive data-sets.

The empirical study reveals some useful insight on link quality fluctuation for static and mobile scenarios. In static deployment, long-term fluctuation over a period of time is observed and link losses and successes show repeated patterns. The reason for these patterns is a gradual change in the environment (the result of experiments conducted in building lobby and garden during non-busy hours). However, in case of a rapidly changing environment, link quality shows short-term link fluctuations (the result of experiments conducted in cafeteria during busy hours). Chapter 3 describes in detail the empirical study of wireless channels and presents a detailed analysis of link quality fluctuation for wireless sensor networks.

2. **An Offline Approach: Link Quality Estimation Model for WSNs (Chapter 4)**:

These empirical studies confirm that link quality fluctuates considerably even in a static deployment. Hence, understanding stable durations, good and bad alike, can contribute to the efficient transmission of packets. Most existing, off-the-shelf transceivers make link quality indicator metrics available to higher-layer services including the received signal strength indicator (RSSI), the link quality indicator (LQI), and the background noise level. Unfortunately, it is not possible to establish deterministic relationships between these metrics and successful packet delivery. Packets can be successfully transmitted with a certain probability even when the metrics indicate that the link is bad and vice versa.

To model the long-term link quality fluctuation in a static scenario, two offline approaches are proposed, one based on conditional probability, and another on a two-stage Markov model. These offline approaches show that in static deployment link quality fluctuation statistics can be regarded as stationary in a wide sense. Therefore, periodicity in the link quality fluctuation can be exploited to design communication protocols. The first model uses a conditional distribution function to describe the reliable and unreliable duration of a channel. The second model uses k-mean clustering to describe link quality fluctuation onto countable regions. Afterward, state transition probabilities are calculated offline on the basis of the relationship between ARR vs. SNR statistics. The probability density function of each state is used to calculate the expected duration of each state.

The results of the experiment confirm that this approach improves the packet success rate of wireless links. This approach improved the packet success rate of the links by up to 40% when compared with the baseline approach and by up to 25% when compared with the state-of-the-art approaches.

3. **A Hybrid Approach: Link Quality Estimation Model for WSNs (Chapter 5)**:

   The advantage of the offline approach is that it estimates the quality of the link over an extended period of time due to no constraint on memory and computation. However, the offline model is unable to capture any short-term changes in link quality given that state transition is calculated offline and is constant. Hence, it is possible the model will make wrong transitions or will fail to "perceive" short term link quality fluctuations.

   To address this shortcoming of the offline approach, I propose a light-weight, hybrid approach in this thesis that takes advantage of both offline and online models. The aim here is to characterise the long-term link quality fluctuation with statistics that are obtained offline. I also seek to employ the statistics of the received acknowledgement packets to deal with short-term link quality fluctuations. This approach uses burst transmission to gather sufficient data and to use these data for determining when and for how long nodes should transmit packets in burst. It also determines the expected duration for which the nodes should abstain from transmitting packets when the link quality is bad. The online statistics are used to fine-tune and calibrate the offline model. This hybrid approach increases the throughout to 35% in comparison to the offline approach.

   Chapter 5 describes the detail architecture of the proposed hybrid estimator and provide evaluation results.

4. **Online Approach: Link Quality Estimation Model for MWSNs (Chapter 6)**:

   Supporting mobility during burst transmission is critical for many applications, such as healthcare where biomedical sensor nodes can be attached to the bodies of patients to monitor their activities and vital signs, as well as to collect and disseminate data. In mobile wireless sensor networks (MWSNs), the link quality fluctuates more rapidly as compared to static deployment due to changing environments, path-loss, fading, Doppler effect, and shadowing. One of the bigger challenges of mobile scenarios is to cope-up with impulsively changing link quality.

   In chapter 6, the mobility of sensor nodes and its effects on link quality fluctuations are taken into account. First, an extensive empirical study with different mobility patterns in different environments is performed. The empirical study reveals that link quality is highly affected by mobility and that link losses have no correlation as the mobility patterns are non deterministic. Therefore, link quality fluctuations cannot be regarded as stationary. Furthermore, the statistics established offline may not accurately represent the current link quality fluctuations, as it is impossible to accurately emulate or reproduce movement patterns. Hence, the duration of the good and bad states should be estimated online. Fortunately, compared to the speed of the mobile node (if the mobile node is carried by a human being), the packet transmission rate is higher, so it is possible to gather enough data to predict short-term link quality fluctuation.

I propose an adaptive burst transmission (ABT) protocol which models the link quality fluctuation in real time by estimating the durations of good and bad states from the statistics of incoming ACK packets. To improve the quality of prediction, adaptive history size is employed which ensures a high percentage of fresh values in a history array. Furthermore, ABT enables neighbouring nodes to share information pertaining to link states and, thereby, to achieve better channel usage. This approach achieved a reduction of 20% to 52% end-to-end delay and also reduced packet loss by 14% to 48% in comparison to Baseline approach.

Chapter 6 describes in detail the architecture of ABT, a MAC-layer solution, its implementation on TelosB platform, and detailed results on the performance of ABT protocol.

1.4 Organisation of the Thesis

The remaining part of the thesis is organised as follows: In chapter 2, a detailed review on link quality estimation, bursty links, and transmission schemes proposed to deal with bursty links are presented. Chapter 3 discusses an empirical study of link quality fluctuations, especially link burstiness under different scenarios. The observations made in this chapter provides the basis of my approach to address link burstiness for wireless sensor networks. Chapter 4 discusses two offline approaches to model link burstiness by taking into account a large set of link quality data from different environments. Chapter 5 is about a hybrid approach which takes advantage of both offline and online approaches. Chapter 6 analyses the design and implementation of an online burst transmission scheme by modeling short-term link quality fluctuations in real time. The impact of sharing link quality information among neighbouring nodes on channel usage and throughput is also reviewed. In chapter 7, a comparison of the performance of all the approaches in this thesis are addressed by conducting experiments in static and mobile scenarios. Finally, chapter 8 provides some concluding remarks and open challenges which can lead to future work.

All the results presented in this dissertation have been peer-reviewed, published, and presented at international conferences and workshops. The associated publications are listed at the beginning of the dissertation (List of Publications) and referenced in corresponding chapters.

Chapter 2

Related Work

In this chapter, prominent studies related to link quality estimation, bulk/burst transmission protocols, and burstiness of wireless links for static and mobile environment are covered. The work in this dissertation builds on the ideas from these research areas and seeks to resolve some open issues.

2.1 Burst Transmission in WSNs

The enormous growth in the different applications of wireless sensor networks and the emergence of the Internet of Things (IoT) creates the need to support high throughput. Existing physical and medium access control protocols in wireless sensor networks support low data rate communication to favour low-power operations. For many applications they are adequate, since the processes which should be monitored by the wireless sensors (temperature, light, humidity, barometric pressure) change slowly over time. Hence, it suffices to sample the sensor at long intervals. Newly emerging applications, on the other hand, in the area of health care, wildlife monitoring and unmanned vehicles require relatively high throughput. In many real time monitoring applications such as the patient monitoring system [AE10], sensors are attached to the patient to monitor vital parameters. These sensor nodes generate time-series data at high sampling rates, resulting in bulk sensor data. The data typically ranges from ten to one hundred kilobytes. It needs to be transmitted to the base station where the doctor can further analyse the data and monitor the health progress of a patient. Table **??** summarises

Accelerometer	1.5 Kbps
Gyroscope	9.6 Kbps
ECG	8.4 Kbps

Table 2.1: Typical Data Rates of Motion and Medical Sensors[FMBL13].

the data rate requirement for different sensors. The storage and power limitations of the sensor nodes create the need to transfer the bulk sensor data immediately to avoid overflow and data loss. The main idea is to assign the channel exclusively to only one transmitter until all the accumulated packets in the buffer have been transferred. This exclusive use avoids aimless contention and significantly reduces packet transmission latency by dispensing with repeated clear channel assessments, random back-off, and the transmission of RTS and CTS packets for every single packet.

2.2 Burst Transmission Protocols

The need to meet the demand of high throughput for static and mobile applications in wireless sensor networks has given rise to a new batch of MAC protocols, namely burst transmission protocols [SRP+07],[D08],[BKSV10], [SOFA11], [DC14].

Kim et al. [D08] propose FLUSH, a multi-hop bulk data transport protocol for wireless sensor networks. It is a result of a cross-layer design with the assumption that a single active flow should be supported in a network, which connects a source node with the base station (the sink). Flush uses a dynamic rate-control algorithm in each hop along the path towards the sink in order to avoid intra-path interferences. The dynamic rate control algorithm adopts a snooping strategy and requires no extra control packets.

Raman et al. propose PIP (packets in pipe) [BKSV10], a TDMA-based approach to transfer bulk data in a multi-hop network. PIP uses TDMA, multi-channel operations and conditional immediate transmission technique proposed by Osterlind et al. [LSKS09a] to achieve a high throughput. PIP assumes that the underlying link quality is stable and all the nodes participating in the transfer are always active (on) during the data transfer. This can be a potential cause of resource wastage.

Jeong at al.[JSGS16] propose an asynchronous burst transmission MAC protocol to solve channel contention and hidden terminal problem for IEEE 802.15.4 networks. Their protocol works on data packet overhearing in which each transmitter broadcasts its queue length (number of packets to transmit). The neighbouring nodes who wish to transmit, overhear the data packet, and in response, sleep for the period of time that it takes the current transmitter to finish all of its packet transmission. Afterwards, the nodes wake-up to contend the medium again. The authors have shows how their scheme improves the packet reception ratio and duty-cycle of the nodes. However, their scheme does not take into account the link quality fluctuations and consider the under lying link quality to be stable. This is not actually true.

Pyeon at al.[DH17] propose an efficient burst transmission using a multi-path pipeline strategy for multi-hop sensor networks. They address the problem of unreliability in pipeline transmission as the presence of a single bad link along the path can stall the transmission completely. The cycle-time (time required to transmit packet from source to destination) is adjusted by each node on the path. This allows the nodes to retransmit the lost packet avoiding pipeline stalling and improving energy efficiency of the network. However, leveraging extra slot and real time computation of cycle-time is costly in terms of energy efficiency and transmission delay.

The focus of the above protocols is to achieve high throughput. But these protocols do not take link quality fluctuations into consideration even though link quality fluctuations are one of the most significant challenges for wireless links, particularly, for those links established between mobile nodes. Duquennoy et al. [SOFA11] address this problem and propose a generic burst-forwarding (BF) technique which combines duty cycle with high throughput in bulk data transfer. BF employs a two-level retransmission scheme to overcome isolated and consecutive losses. At the first level of retransmission, a lost packet is retransmitted immediately. If retransmitted packets are lost repeatedly within a fixed period of time, the MAC layer stops burst transmission and backs-off using CSMA/EB.

In [HHD10], the authors employ a Hidden Markov Model (HMM) to estimate the durations of poor channel quality (what they call, a push-back period). They find that if a transmission is successful, the next packet will be transmitted immediately; if, however, a transmission fails, then the next transmission is pushed back by k-slots.

One other way of dealing with link quality fluctuation and aimless contention is to employ diversity schemes where one and the same packet is simultaneously transmitted by many senders to multiple receivers. Recently, several researchers [DC14, FZLO11, DCL13] have proposed synchronous transmission in order to exploit the Constructive Interference (CI) and the Capture Effect (CE) phenomenon in order to improve the throughput of the system and mitigate link losses. However, this approach requires strict synchronisation. These approaches may provide high throughput, but it is at the cost of high power consumption.

2.3 Link Quality Fluctuation

One factor which considerably affects the performance as well as the lifetime of wireless sensor networks is link quality fluctuations. Link quality fluctuations can reduce throughput, increase packet delivery latency and energy cost, due to the retransmission of lost or corrupted packets. This is particularly true for wireless sensor networks which are deployed in harsh environments. The term "harsh" should be understood broadly, for many urban deployments (such as for traffic monitoring, pipeline monitoring, structural health monitoring) where human and car movements are regular and can experience a large packet loss rate [KPAP10]. The quality of a radio signal is highly dynamic and changes over time. Several factors that impact signal quality are environment, hardware, interference, and mobility.

2.3.1 Environmental Factors

The propagation of radio signals depends on the type of environment in which it operates, such as indoor (home, office, building lobby) or outdoor (streets, garden, bridges). Environment factors include path-loss, multipath, and shadowing.

- **Path-loss:** In wireless communication, path-loss is defined as the reduction in the power of an electromagnetic wave as it propagates through free space. A path-loss model calculates the received signal strength at a certain distance from the transmitter. This can be expressed as [TV05]:

$$L = 10n \log_{10}(d) + C \tag{2.1}$$

  where **L** is the path-loss in decibels, **n** denotes the path-loss exponent, **d** is the distance between the transmitter and the receiver and **C** is a constant for system losses.

- **Multipath:** Multipath is the phenomena in which the radio signal travels using different routes to reach the receiver. The main factors that cause multi-path are scattering, reflection, refraction, and diffraction.
- **Shadowing:** The phenomena in which a radio signal is obstructed by a large object is called shadowing.

2.3.2 Hardware

Wireless sensor nodes employ simple radio chips such as (CC1000,TR1000,CC2420 and CC2500) due to a low-power constraint. These radio chips transmit low-power signals which are highly affected by internal noise, interference, and multipath. The widely used sensor nodes, TelosB/TMote sensor, are equipped with a low-gain antenna printed on the board providing irregular radiation patterns and resulting in non-uniform communication range [NAL+12].

2.3.3 Interference

The radio signal can also be hampered by RF interference. The source of interference can be internal or external. Internal interference occurs when two sensor nodes transmit at the same time (concurrent transmission). While external interference occurs due to cross technology such as Bluetooth (IEEE 802.15.1) and WiFi (IEEE 802.11) that operates on the same frequency band as low-power IEEE 802.15.4 [AHS14].

2.3.4 Mobility

Mobility of sensor nodes are essential for many applications in wireless sensor networks in areas such as the healthcare system, animal monitoring and tracking, and home automation. Mobility deteriorates the quality of the radio signal considerably resulting in high packet losses. When sensor nodes move, several factors can affect the link quality, including the sudden shake of a node, a big blockage between transmitter and receiver, or random antenna directions.

Link quality fluctuation is usually taken care of at physical and MAC layer. At the physical layer different strategies have been proposed, such as dynamic rate adaptation [SRRK06, JR07, AA01, LMP09], dynamic channel allocation [RAH00, ASYC02, EDZ09], dynamic transmission power [CMdS+07, SJG+06, SVA08, PW13, LLK14, SKLC14], and frame and synchronisation error [MVD13, DCHZ16, CDZG17] to estimate the packet delivery ratio. Alternatively, link quality fluctuation at the MAC layer is estimated by employing link quality estimators [JR03, BMPC08, NAH+10, AAV+10] which will be discussed in detail in the next section.

2.4 Link Characterisation

Several empirical studies exist on the characterisation of link quality fluctuation and on link quality estimation [SAAP08, HOL+09, JLX02, DJS+04]. These studies broadly classify a link as (a) connected, where links are highly reliable, symmetric and stable, (b) transitional (intermediate), where links suffer from frequent fluctuations in quality and, hence, they are considered as unreliable and bursty, and (c) disconnected, where links are of very poor quality and communication is not possible. The metrics they use for classification are among others RSSI, LQI, SNR, packet reception rate (PRR), and acknowledgment reception rate (ARR). In connected links, packets can be transmitted with high probability ($> 90\%$) and in disconnected links, packet can be transmitted with low probability ($< 10\%$) [KPAP10] see figure 2.1. In an intermediate link, however, packet/acknowledgment reception rate is a random variable and the relationship between packet reception rate and any of the link quality parameters (RSSI, LQI, SNR) is never deterministic. Most studies assert that typical wireless channels describe the intermediate quality link [TP09a, BKN+13]. Some important metrics that characterise link quality for sensor networks are:

- RSSI (Received Signal Strength Indicator): Many radio transceivers (e.g CC2420,CC2420 etc.) provide the signal strength of the received packet through a built-in 8 bit RSSI register. The RSSI value is average over an 8 symbol period (128μs) and will be valid after the receiver has been enabled for at least 8 symbol periods [CC207].

- LQI (Link Quality Indicator): The LQI is another hardware metric provided by radio transceivers which measures the strength of received packets. The LQI estimates how well the received signal can be demodulated by calculating the error magnitude between the ideal constellation of O-QPSK and the receive signal over the 64 symbol period. If the error is high, the LQI value will be smaller and vice-versa [CC209].

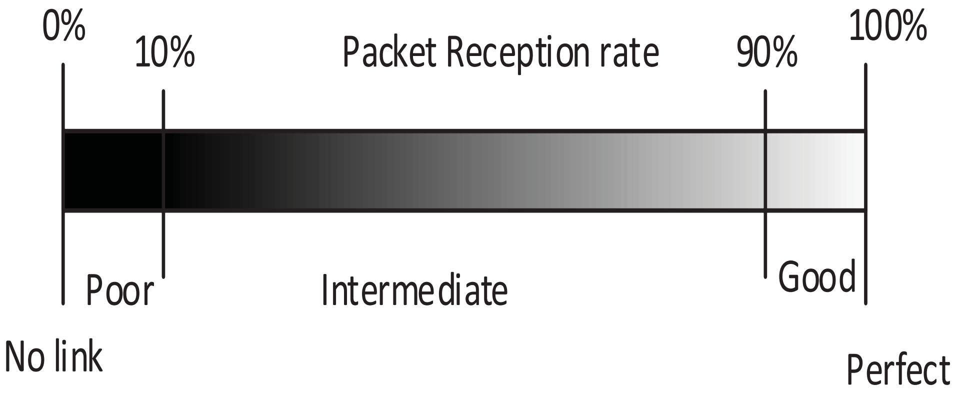


Figure 2.1: Link Definition. A link is dead if it has a packet reception ratio (PRR) of 0%. A link is poor if the PRR is less than 10%, intermediate if the PRR is between 10% and 90%, good if the PRR is between 90% and 100%, and perfect if the PRR is 100%[KPAP10]

- SNR (Signal to Noise Ratio): The SNR metric is widely used to characterise the link quality of received packets. It is defined as the difference in decibel between the RSSI of received packets and background noise. Unlike the RSSI, the SNR contains information pertaining both to the received signal's strength and to background noise.
- PRR (Packet Reception Ratio): The PRR is defined as the ratio of the number of successfully received packets at the receiver to the total number of packets transmitted by the transmitter.
- ARR (Acknowledgment Reception Ratio): The ARR metric is similar to the PRR but calculated on the sender side and defined as the ratio of the number of successfully received acknowledgment packets to the total number of packets transmitted.

In an intermediate link, however, packet/acknowledgment reception rate is a random variable and the relationship between packet reception rate and any of the link quality parameters (RSSI, LQI, SNR) is never deterministic.

2.5 Bursty Links

Link burstiness is a phenomenon in which the channel stays stable[1] for a period of time. At the physical layer, this phenomenon is called channel coherence time [Gol05]. The channel

[1] It should be noted that stable does not imply good. It simply means that the quality of the link in this duration can be considered unchanging

coherence time is defined as the time over which the channel responds to the signal in the same way over a period of time. In other words, coherence time T_c is the duration in which two different signal receive have a high magnitude correlation. Coherence time is given as [DV05]:

$$T_c = \frac{1}{f_m} \tag{2.2}$$

where, f_m is a maximum Doppler spread or Doppler frequency.

At the MAC layer, link burstiness is a measure of successfully transmitting and lost packets in succession. If the packets are successfully transmitting or lost in succession, the link is considered as highly bursty. To achieve reliable communication link burstiness needs to be measured, as it can affect the performance of protocols. For-example, immediate retransmission applied to lost packets is of no use and costs high- energy consumption. Another observation reveals that wireless links have high temporal correlation and bursty characteristics. The same has been observed by several researchers in the past [DJS+04, SAAP08]. Due to the energy constraint of the sensor network, it is quite important to design transmission strategies efficiently by taking channel condition into consideration, as most of the power is consumed in transmitting/retransmitting the packets.

2.6 Link Quality Estimation

Link quality estimation is a fundamental building block for higher layer protocols such as MAC and Routing. To measure the dynamic nature of wireless channels, link quality estimators (LQE) have been proposed by several studies [LMD05, YML07, AAV+10, LE11, TE14]. Numerous empirical studies [SL06, KPAP06, KPAP10] investigate the metrics provided by IEEE 802.15.4 radio transceiver namely, the RSSI, LQI, SNR, and PRR to estimate the link quality. The researchers concluded that RSSI and LQI metrics can provide quick and accurate estimates of the quality of a link: if it is high or if it does not even have a single packet input. However, these metrics are poor estimators of intermediate quality links [LPM+10, BKN+13]. The RSSI is the sum of the pure received signal strength and the noise floor at the receiver, where the SNR shows how strong the received signal strength is in comparison to receiver noise. The SNR metric-based link quality estimator is better than the RSSI-based estimator

[KPAP10, BKN+13].

2.7 Link Quality Estimator (LQE)

There are two types of LQEs existing in WSN, namely hardware-based and software-based. Hardware-based LQEs (H-LQE) use physical layer information (LQI, RSSI, and SNR) to estimate the link quality [NAL+12]. The H-LQE has the advantage of having no additional overhead incurred as the parameters can be read directly from the received packets using a radio transceiver chip (e.g. CC2420). However, several research studies [NAL+12, LMH+03, BKJ+09, SL06, TE14] report that the H-LQE is unable to estimate the link quality accurately due to a number of reasons. Physical layer parameters can classify the link as either good or bad, however, they are unable to categorise those links with intermediate quality (links in the transitional region). The key reason for this is that the physical parameters are extracted only from those packets which are successfully received. These parameters do not account for packet loss resulting in a overestimation of radio link quality.

The software-based LQE (S-LQE) is classified into three different categories [NAL+12]. The first is Packet Reception Ratio (PRR) based. This is a receiver side estimator calculated as ‘‘the number of successfully received packets to the total number of transmitted packets with in a specific observation window-size’’. Researchers often combined the PRR metric with the H-LQE [TE14, BRAR14, LX15] to predict and estimate the link quality. A basic problem of a PRR based metric is estimating link quality on the basis of the past history of several packets. As the link quality changes abruptly, the PRR metric does not perform well in predicting and estimating the intermediate or short-term link quality. Conversely, the PRR based metric is suitable for monitoring long-term link quality. The second category is based on the Required Number of Packet re-transmission (RNP), proposed by Cerpa et al. [LMD05]. This is a sender side estimator calculated as a ratio of “the number of transmitted and retransmitted packets to the number of successfully received packets minus 1 (to exclude the first packet transmission), within a specific window-size’’. Several research studies [LMD05, BKJ+09] compared PRR-and-RNP-based metrics and claim that the RNP metric performed better than the PRR metric because the RNP based LQE provides a fine-grained estimation by taking into account the loss packets. The problem with a PRR-based LQE is that it overestimates the link given that it is unaware of the exact packet loss location in the estimation window and the total number of retransmitted packets required for successful reception to occur. Similarly, the RNP metric depends on the feedback of the receiver through acknowledgement packets and therefore it may lose acknowledgement packets due to the asymmetrical property of wireless links resulting in an underestimation of the link quality [BKJ+09]. The Last category is the Score-Based LQE, a hybrid estimator combining both H-LQE and S-LQEs. These estimators combine several link quality metrics to calculate the score that shows the overall quality of the link. Several Score-Based LQEs [TE14, AAV+10, LE11, NAH+10, YML07, XC06] were proposed in a number of studies. The performance of score-based estimators is better than hardware and software based LQEs due to the hybrid approach, but at the expense of a higher complexity.

Woo et al. [AD03] proposed the Window Mean with Exponentially Weighted Moving Average (WMEWMA), a receiver-side LQE that approximates the PRR by applying the EWMA filter on the PRR metric to smooth it. Woo and his colleagues found that the WMEWMA performs better than other estimation techniques such as moving average by averaging the EWMA. Following the design of Woo, Fonseca et al., [FGJL07] proposed a four-bit wireless link estimator (4B), a hybrid LQE that combines information from the cross-layer using four bits: the white bit from physical, the ack-bit from data-link, the pin bit and compare the bit from network layers. 4B uses expected transmission count (ETX) [JDJR05] as a link quality metric. Later Senel et al. [SCL+07] proposed the Kalman filter based LQE to estimate Packet Success Rate (PSR) because estimating the PRR by counting the number of successfully received packets required more time and memory, meaning the PRR based estimator cannot respond to abrupt changes in the wireless link. To overcome the poor reactivity of the PRR based approach, they proposed to use a pre-calibrated SNR-PSR map to estimate PSR at the receiver. The received signal strength (RSS) is calculated from each successfully received packet and then put into the Kalman filter which provides an estimation of the RSS. Hence, the SNR is calculated by subtracting the noise floor from the estimated RSS. In the last stage, the pre-calibrated SNR-PRR curve is used to estimate the PSR. The authors of this study claim that their estimator can provide fast estimation, using only a single received packet.

Boano et al. [AAV+10] proposed a triangle metric that combines PRR, SNR and LQI metrics geometrically to estimate how quality of the link fluctuates. As per their observations, the higher the SNR and the LQI values are, the better the quality of the link. The mean SNR and LQI values are presented geometrically on a Cartesian coordinate system and calculate the distance from the origin. This is actually the hypotenuse in a right triangle. The larger the length of hypotenuse, the better is the link quality. Finally, they classified the links as very good, good, average and poor using threshold values for each category.

Later Baccour at al. [NAH+10] proposed a link quality estimator based on fuzzy logic (F-LQE), a hybrid LQE that employs physical layer parameters (SNR) in addition to the PRR metric. F-LQE uses Score-Based Linear Membership Function to estimate the link quality by combining four different link quality metrics: (1) Packet delivery– to compute the link capacity by calculating the smoothed PRR (SPRR). (2) Asymmetry level (ASL)– to measure the difference between the uplink PRR and the downlink PRR. The ASL metric indicates whether a successfully received packet at the receiver can be acknowledged by the sender or not. (3) Link Stability Factor (SF)– to measure the link stability over a period of time. SF is computed as the co-efficient of variation based on the history of 30 PRRs. (4) Channel quality– this is evaluated by averaging the SNR (ASNR) in a window of 'W' received packets given that the ASNR improves the accuracy of link quality estimation. The F-LQE combines different link properties into single metric to estimate the quality of link quality, which gives the F-LQE more stability, making it a reliable estimator compared with the previous existing ones. However, the F-LQE requires more memory to calculate the SF and by combining diverse channel properties, computational complexity increased as well.

Tao et al. [LE11] presented Forsee (4C), a wireless link prediction using link features and a data-driven link LQE that estimates the link quality along with the online prediction. The 4C LQE model consists of three phases: (1) The data collection phase involves a-priori gathering of link quality data in the intended environment. (2) The offline modelling phase includes an offline training prediction model and selection. Three different prediction models based on different machine learning methods were presented. These model included the naive Bayes classifier, logistic regression and artificial neural networks. (3) With online prediction, these models input a combination of the PRR and the physical layer information (RSSI, SNR and LQI) and predict the success probability of receiving next packet. The 4C estimator outperforms other link estimators due to its feature of predicting the success probability of receiving the next packet and the fact that it requires less data to train the predicting model. The main disadvantage of the 4C is that it requires a collection of link data from the target deployment

Table 2.2: Comparison of Link Quality Estimators.

Estimator	Approach	Monitoring	Deployment	Estimate Link Burstiness
PRR	Average data packets	Offline/Online	Static	**No**
ARR	Average acknowledgement packets	Offline/Online	Static	**No**
RNP	Average acknowledgement packets	Offline	Static	**No**
ETX	Average data and acknowledgement packets	Online	Static	**No**
Kalman	SNR-ARR prediction	Offline	Static	**No**
WMEWMA	PRR prediction	Offline	Static	**No**
4B	ETX prediction	Offline/Online	Static	**No**
4C	PRR, RSSI, SNR and LQI	Offline/Online	Static	**No**
Triangle	PRR, SNR and LQI	Offline	Static	**No**
F-LQE	Fuzzy logic	Offline	Static	**No**
TALENT	Stochastic Gradient	Online	Static	**No**

site to complete offline training of the prediction model. In a more recent study, Tao et al. [TE12] proposed the TALENT (Temporal Adaptive Link Estimator with no Training) that uses stochastic gradient descent (SGD), an online learning algorithm which can train a logistic regression (LR) model. By using online learning, they overcome the disadvantage of collecting data for training the model. TALENT performs better than statistically trained models as it predicts the future link quality of intermediate links. The limitation of this approach is that it predicts the fate only of a single packet and uses complex algorithm like the SGD for online learning. These require high computation power. Table 2.2 summarise the link quality estimators discussed above.

2.8 Approaches to Dealing with Bursty Links

Bursty links are those in which packets successes and failures are highly correlated, meanings packets are either transmitted successfully or lost in burst. Bursty links switch between good and poor quality. These fluctuations in a wireless link affect the protocol performance considerably. Therefore, many efforts have been made to chracterise the burstiness of wireless links. The first such effort to model loss burstiness on wired networks is proposed by Jiang et.al[JS00].

Table 2.3: Comparison Between Approaches Dealing with Link Burstiness.

Approach	Advantage	Disadvantage
Offline	1. Large memory footprint 2. High computational power	1. Unable to deal with short-term link quality fluctuation 2. Fixed solution
Online	1. Estimate short-term link quality fluctuation 2. Adaptive solution	1. Less computation power 2. Large overhead 3. Small memory footprint
Hybrid	1. Large memory foot print 2. High computational power 3. Estimate both long and short-term link quality fluctuation	1. Large overhead

A 2-state Gilbert Elliot model with an inter-loss distance (ILD) metric is used to characterise loss dependency. The model is applied to VoIP data trace and found rarely consecutive losses, sized 5 packets or less. Furthermore, Syed et al.[AH03] propose a 9 Order Hidden Markov Model (HMM) to model bit error rate and consecutive packet losses for a wireless link. They suggest a higher Order Markov Chain Model, where the link behaves more abruptly in comparison to full-state and hidden Markov Chains. However, the complexity of these models is too high and not suitable for a real-time system. Later, Srinivasan et al.[SAAP08] proposed a β metric to compute the burstiness of a link. The β factor of a link measures the of approximation to an ideal link based on CPDF. Liu et al. [LSKS09b] propose a two-state Hidden Markov Model to measure the duration of consecutive losses. Based on this information they push-back the data transmission to overcome periods of poor channel quality and high interference while ensuring that the throughput requirement of an application is met.

The effort of dealing with link burstiness can be divided into three main categories: offline, online, or hybrid approaches. Table 2.3 summarises the comparison between the various link burstiness approaches.

2.8.1 Offline Approach: Long-Term Characteristics

Srinivasan et al. [SAAP08] propose a β metric to measure the burstiness of a wireless link. The β factor is a measure of how close a link is to an ideal bursty link. It is calculated by using the Kantorovich-Wasserstein (KW) distance [JG05], which measures the distance between a conditional probability delivery function (CPDF) of a given link and an ideal link. The CPDF expresses the probability of receiving the next packet successfully after 'n' consecutive successes or failures. The value of β determines the burstiness of the link. A value of $\beta = 1$ and $= 0$ represents a perfectly correlated link and an uncorrelated link, respectively. To explore the performance of the β metric, the authors proposes a transmission control scheme which is intended to increase the packet reception ratio by sending packets in bursts until they encounter a failure. When a failure is detected, transmission is halted for fixed period of time. The limitation of this approach is the large amount of data required by the algorithm to predict the success of the next packet. However, it cannot determine the length of reliable and unreliable transmission periods, which are important to efficiently schedule packet transmissions. Also, β does not handle short-term link quality fluctuations given that it considers all types of failures as similar. Alizai et al. [AWK+11] also argued that this algorithm is not suitable for online estimation as it requires a large amount of data to achieve a 95% confidence interval.

Alizai et al.[HOL+09] propose a short-term link quality estimator (STLE) based on conditional success. A STLE is based on the heuristic that any link becomes reliable for packet delivery if the last three consecutive packets were successful on that link regardless of the overall PRR of that link. They also find that short-term link quality fluctuation often has bursty nature (packet losses are highly correlated). The STLE is integrated with the Bursty Routing Extension (BRE) to take advantage of short-term reliable links to reduce routing cost and transmission delay.

Rusak et. al.[TP09a] investigate the time-varying characteristics of wireless channels at the physical and link layers. According to their observations, PRR analysis at different time scales shows wireless channel to be characterised as bursty rather than constant. This can be understood by observing the change in the packet reception rate (PRR) over time. To analyse and characterise the bursty nature of wireless channels, the authors uses Wavelet Transform on received signal strength indicators (RSSI). Wavelet analysis describes the coherent structure in the signal under observation. The analysis reveals that burst time spans are periodic and identical in nature.

Munir et al. [SSE+10] define link burstiness as a period of continuous packet losses and propose a scheduling algorithm which produces latency bound for real-time periodic streaming a large amount of packets. The authors introduce B_{max} and B_{min} to characterise the maximum number of consecutive packets losses and the minimum number of consecutive packets successes, respectively. To calculate these metrics, they performed an empirical study for 21 days and collected traces of packet successes and failures for different links. An offline packet transmission schedule then computes the transmission and intermission periods based on B_{max} and B_{min}. The authors note that the most frequently observed consecutive success is $B_{min} = 1$ which means the transmission scheme should transmit a single packet followed by an intermission period which corresponds to B_{max}. This, however, does not correctly reflect the condition of most real links where good and stable links can be observed.

Wen et al.[WAD15] propose an offline transmission scheme that uses the conditional probability distribution function of SNR fluctuations to estimate the expected reliable and unreliable transmission periods. Their approach employs an SNR threshold above which a link is considered to be good and stable. However, empirical studies reveal that the SNR varies between 3dB to 21dB in most intermediate links in which case the approach of Wen et al. potentially results in under- and overestimated burst periods. Here, the expected burst-size is fixed, as the proposed scheme regards only the long-term link quality fluctuation. However, the conditional distribution function is obtained by empirically define SNR thresholds, which may not be applicable for different types of links.

2.8.2 Online Approach: Short-Term Link Quality

Brown et al.[JBU+11] introduce BrustProbe, a mechanism to measure link burstiness online. Probing slots are embedded at each epoch to measure the link burstiness B_{max} and share this information among the neighbouring nodes. The probe mechanism is more reactive for capturing burst period due to online probe sharing, but it increases the energy consumption and duty cycle by 2%. BrustProbe can also fail to capture packet losses as the link is estimated for the fixed duration in each epoch. Therefore, if the link losses do not occur in the estimation slot, it is possible to overestimate the link quality.

In [VPH+10], the authors use the SNR values of RTS/CTS control messages to learn about the current state of a link and to decide whether data packets should be transmitted or withheld. The decision is made by employing a Markov decision process (MDP). The problem with this approach is its reliance on control messages which can cause a considerable overhead in wireless sensor networks, where the size of the data packet is comparable to the control packet. In [WQZQ13], the authors propose cooperative communication between sensor nodes to take advantage of the diversity gain in order to overcome the effect of fading channels.

Alexander et al.[BLKW08] estimate the short-term reliable and unreliable link quality based on overhearing data packets. The authors use a CPDF function to predict the probability that the next packet will be successfully transmitted. They argue that the link is considered reliable if the preceding four packets were successfully transmitted. This heuristic method predicts that the link reliability is similar to the STLE, except, with this method, four consecutive successes are needed rather than three. However, the limitation of this approach is that it can only predict the fate of a single packet. Aditionally, due to its overhearing working principle, it needs to keep its radio on the entire time, ultimately increasing the power consumption of the sensor node.

Caro et al. [DKF+13] propose a machine learning technique to estimate the quality of the wireless link. They use the PRR and the feature vector as a link quality metric. The feature vector includes local measurements of the traffic, topology, signal strength and local network configurations. The algorithm applies supervised incremental learning for regression mapping between the local network configuration and the expected link quality. The mapping information is shared between neighbors to speed up the learning of each individual node which is then used to predict the online link quality.

Li et al. [YDG+13] propose a discrete-time Markov model to estimate the burstiness of a wireless link. The transition probability is used to predict the future of the next packet. Packet success and failure shows different states of the HMM model. The model does reverse engineering by taking β values as an input and provides burstiness traffic trace as an output. The trace clarifies both the positions and pattern of link successes and failures which cannot be obtain by β value online. The data trace can further be used to simulate the bursty behaviour of wireless links as shown in [MK17].

Alizai et al. [AWK+11] combine two different metrics to characterise link quality fluctuation and to determine the number of packets that can be transmitted in burst. These are the MAC_3 and the expected future transmission (EFT). The MAC_3 is calculated by taking the moving average of incoming acknowledgement packets (the window for the moving average was set to 100). The authors experimentally determined that the probability of successfully transmitting a future packet increased to 80% once the past three consecutive packets were successfully transmitted. The probability does not increase appreciably if the number of successfully transmitted past packets increases. So, the MAC_3 calculates the probability of how many number of packets will be successfully transmitted in the future when three consecutive packets were successfully transmitted in the past. The EFT averages the number of packets that can be successfully transmitted in the future given successful transmission of the three previous consecutive packets. This is set as the burst size. Furthermore the authors argue that β-factor is not suitable for online estimation due to a limited history array. The β-factor produces an estimation error of 83% for a history array of 1000 packets [AWK+11]. While the approach of Alizai et al. is interesting, it has two drawbacks. First, the moving average is slow to "perceive" short-term fluctuations and slow to react to them (as we shall show this experimentally). Second, whereas the number of packets that can be transmitted in burst is determined, it is not clear for how long a transmitting node should pause before the next burst transmission begins.

2.8.3 Hybrid Approach

Sha Liu et.al. [LSKS09a] propose an energy efficient data transmission algorithm called Pushback using the HMM. It delays packet transmissions in order to overcome periods of poor channel quality and high interference, while ensuring that the throughput requirement of the node is met. The main idea of the pushback algorithm is to defer packet transmission for computed period of time upon packet transmissions. If a transmission is successful, the next packet will be transmitted immediately. If, however, transmission fails, the next transmission is pushed back by k-slots. The pushback period k is estimated using the lookup table which limits it to the use of certain cases and channel states. The other problem is that after the differed period k is finished, if the next transmitted packet fails due to independent losses, Pushback will result in unnecessary differed transmissions. The first limitation of this approach is its difficulty in dealing with independent losses as transmission is halted on a single failure (similar to [SAAP08]). Second, the scheme is computationally expensive as extra time is required to calculate the pushback period for each failure. Third, their paper does not clarify the channel observe period or the amount of statistics required from the link to compute the probability of success or failure.

Srivastava et.al [SE10] proposed an Energy Optimal Transmission Scheduler based on the dynamic programming method. The Scheduler uses channel side information(CSI) which can be obtained from sequences of ACK/NACK packets. The authors model the wireless channel as a finite-state Markov channel (FSMC). They not only consider the estimated channel states, but also the transmission queue states in order to make a transmission decision. To make the algorithm applicable to hardware limited in resources, they proposed to pre-calculate the transmission control rules and turn them into a lookup table stored in the sensor memory, instead of calculating during runtime. The drawback of lookup table is it increases the memory utilization. Even worse, when the number of FSMC states increase, the memory use will increase exponentially.

2.9 Discussion and Comparison

Table 2.4 compares the three most important features of bursty link estimators. Discussed in this section are the merits and demerits of the bursty link estimator in detail. The β-factor estimates the burstiness of a wireless link and compares it to the ideal bursty link. An ideal bursty link is one in which all the transmitted packets are either successfully received or lost. This defines the nature of link; hence packet transmission can be employed accordingly. If the link is highly bursty then upon losing a single packet, packet transmission should be halted, as there is a high probability of losing the immediate transmitted packet again. The other disadvantage is the requirement of a large amount of empirical data to calculate the link burstiness which requires large memory and a high computational power. The value of β is fixed , and it needs to be recalculated if the environmental and channel parameters change.

The STLE estimates the short stable period by overhearing the neighbouring nodes. The authors argue that if the last three packets are successfully received there is a high probability of receiving the next packet successfully. Therefore, on receiving three packets consecutively, the link is declared reliable for the communication. This assumption cannot hold true for all types of links, especially for intermediate quality links as the link quality varies over a short period of time. Furthermore, STLE cannot estimate how many packets should be transmitted consecutively or in other words, it cannot estimate the duration of reliability. The BLE also has high energy cost as it works on packet overhearing.

Wavelet analysis is used to find self-similar and coherent structures on different time-scales.

Wavelet transform has been applied to RSSI traces of several IEEE 802.15.4 wireless low-power links used to measure link burstiness. The authors observe a high packet loss correlation on both physical and link layers. Furthermore, the correlation has non-trivial characteristics of a self-similar nature. The variance in RSSI is used to characterise the time-scaling of wireless links. The most important finding of this study is that the radio signal power time series of many wireless links is consistent with statistical self-similarity. Their study and findings are similar to the β-factor [SAAP08] as the authors of wavelet analysis suggested that halting packet transmission for 640ms on a packet lost will increase the link reliability. Their scheme neither measures the size of a burst nor deals with short-term link quality fluctuations as transmission is halted on loosing a single packet. Furthermore, the scheme uses only RSSI value to measure link burstiness. This is not enough to describe the link correctly as packet loss can occur even when RSSI value are high due to passing obstacles or any short-term link quality fluctuation.

Latency Bound proposes a scheduling algorithm to provide reliable communication for wireless sensor networks. Latency Bound estimates link burstiness by defining a new metric called B_{max} for the industrial automation process. B_{max} characterises link burstiness by measuring the maximum number of consecutive packet losses over a period of time. B_{max} accounts for both interference and link burstiness and is used to reserve a packet retransmission slot for each packet over the route between the sender and the receiver as a way of managing link burstiness and guaranteeing successful packet delivery. However, the probability of a packet loss after transmission using all the allocated time slots is still high because the value of B_{max} is calculated offline and may change in real time during the network operation. Furthermore, the slot scheduling algorithm becomes complex and consumes more network resources as the number of transmitters increases in the network.

BDT employs a finite Markov channel model (MDP) to model link burstiness and Channel Aware Back-Off in conjunction with the Markov chain to give priority to those transmitters with better channel conditions. BDT decide whether to transmit the lost packet immediately or not and the decision is based on the condition of the channel. If the current channel condition is above the specific threshold, the packet will be transmitted immediately. The MDP is used to obtain the optimal threshold for successful packet transmission. RTS/CTS is used before transmitting each packet. RTS/CTS control packets (in addition to data packets) measure link quality. This induces a large overhead, especially in sensor networks where the size of the data packets is comparable to the size of the control packets. BDT employs a Markov chain which consumes high energy given that calculating transition probabilities in real-time is computationally complex. Their algorithm does not estimate the size of the burst.

Burst Probe resolved the problem of Latency Bound [SSE+10] by embedding the value of B_{max} in the transmission schedule which is used by neighbouring nodes to assess link burstiness in real time. The probe slots are allocated at the end of each period (epoch) within the transmission schedule. They are shared among the neighbouring nodes which in turn increases the transmission latency and end-to-end delay. The burst probe is only able to capture the link burstiness if consecutive packet losses are evenly distributed given that link burstiness is calculated at the end of each period over a fixed period of time. The authors assume that link burstiness is evenly distributed which is not the case in real deployment especially as it concerns short-term link quality fluctuation.

The MAC_3 estimates link burstiness by using a conditional packet delivery function and argues that the β-factor is not suitable to estimate link burstiness online. The authors define another metric called Expected Future Transmission to calculate the number of packets required to be transmitted in burst. The EFT is calculated by averaging the number of consecutive success over a fixed period of time. However, this approach is limited to dealing with short-term link quality fluctuation as the size of the history array is fixed. For example, if the history array is filled with zeros, the algorithm used to calculate link burstiness and the EFT will get stuck with the null value. It will need long time to recover from the situation. This reduces the network throughput considerably. This problem can be overcome by adapting the history size in real time based on estimation error and also by defining the minimum burst-size required for a worst-case scenario. MAC_3 does not define the bad channel duration (the number of packets that should be halted before transmitting again).

BF deals with both isolated link losses and short-term link quality fluctuation by utilizing two-level transmission. BF does not stop packet transmission unlike many other transmission schemes on single packet loss. It assumes the channel is reliable for communication until it has 4 consecutive packet losses therefore it retransmits the lost packet 3 times after which the packet transmission is halted using increasing back-off. The limitation of the approach is its inability to model the reliable and unreliable link duration as no estimation of burst size is made. Furthermore, BF strategy performs poorly on intermediate quality links as increasing back-off is applied to cater dynamic link fluctuation.

TALENT uses machine learning technique to predict the link quality in near future. The scheme utilizes online learning techniques such as SGD to train the prediction model to adapt to link quality fluctuation without the need for training data. The author argue that only most recent packet can contribute to accurate prediction therefore their model take most recent packet as an input to predict the fate of next packet. This assumption does not hold especially in intermediate quality links where link quality fluctuates frequently as evident from the empirical results and past studies [SAAP08,]. The correct size of history array to get accurate prediction is still an open issue with no definite answer to it. However, the size of the history array to get accurate prediction is highly related to the estimation error, if estimation error is high then history size should be reduced to give more weight to the recent values.

Pushback estimates the duration of poor channel quality offline utilizing hidden markov model (HMM) based channel model. The algorithm transmits next packet immediately if the current packet is successfully delivered. In case of packet loss it delays the transmission for k number of slots. The value of k is calculated offline and stored in a lookup table corresponding to channel parameters and transition probabilities to avoid complex calculation in real-time. The limitation of pushback is similar to many other protocols as it halts the packet transmission on single failure. The other disadvantage is high computation complexity as transition probabilities are calculated online.

CATS schedules packet transmission based on channel side information (CSI) feedback from the receiver. The channel is modeled using finite state markov chain (FSMC) based on the feedback (CSI) to the controller. The controller decides to schedule the next packet immediately or defer the packet transmission for k slots. The decision is made before transmitting each packet. The decision rule for the controller is made on dynamic programing and CSI. The limitation of the approach is CSI using error free channel between the transceivers which in reality does not exist. Furthermore, the memory requirement for storing state action and transition probability increases exponentially with channel states.

Table 2.4: Comparison Among Bursty Link Estimators.

	Approach	Methodology	Self Adaptive	Estimate Link Burstiness	Estimate Burst Length
β-factor	CPDF	Offline	**No**	**Yes**	**No**
STLE	Conditional success	Offline	**No**	**Yes**	**No**
Wavelet Analysis	Wavelet transform	Offline	**No**	**Yes**	**No**
Latency Bound	Consecutive losses	Offline	**No**	**Yes**	**No**
Binary Decision Based Transmission (BDT)	Markov model and CBA	Online	**No**	**Yes**	**No**
Burst Probe	Consecutive losses	Online	**Yes**	**Yes**	**No**
MAC_3	Online CPDF	Online	**Yes**	**Yes**	partially
BF	CSMA/IB	Online	**No**	**Yes**	**No**
Pushback	Markov Model	Hybrid	**No**	**Yes**	**No**
Channel Aware Transmission Scheduler (CATS)	dynamic programing	Hybrid	**No**	**Yes**	**No**

2.10 Observations and Open Issues

Burst transmission is a key to meet the high throughput demand of an emerging IoT application in wireless sensor networks such as healthcare, data collection, home and industrial automation, and vehicle-to-vehicle communication. However, the underlying link quality of wireless links plays a vital role in achieving energy efficient and reliable communication. Due to importance of link quality dynamics to achieve reliable communication, the link quality fluctuation needs to be taken into consideration for burst transmission protocols. Most of the proposed burst transmission protocols investigated earlier try to model link burstiness by estimating the consecutive failure based on offline, online and hybrid approaches. Previous studies shows that low-power links have high temporal correlation in both static and mobile nodes deployment.

Empirical studies reveals that link quality varies considerably over a period of time in all deployment scenarios (indoor and outdoor). The experiment results further suggest a need for an efficient burst transmission scheme which can deal with dynamic link quality fluctuation. The study also suggests that some links have periodic packet success and loss pattern due to a periodic ON and OFF cycle of noise or interferer (e.g. microwave ON-OFF pattern). These types of links can be considered statistically stationary (at least in a wider sense). It suffices to observe the process for a certain period of time to obtain the distribution or the density function and with it to determine the period. However, other links have a highly dynamic link quality due to the aggressive nature of the interferer. Such is the case of wifi or if a node is mobile. In such cases, the link quality cannot be regarded as stationary. Therefore, the statistics established offline may not be a true estimate of the link quality. The burst size needs to be estimated in real time. The limited size of a sensor node and its limited resources put significant constraints on the complexity of the burst size estimation used to estimate the link quality.

My analysis suggests that packet correlation and periodicity of link fluctuation can be exploited to improve the throughput and energy consumption of burst transmission techniques. For example, knowledge of good and bad durations of the link quality will reduce the packet retransmission cost by avoiding packet transmission during the bad phase. Alternatively, it will also improve the throughput by transmitting packets in burst when the link quality is good. Hence, I conclude that most of the proposed burst transmission protocols do not fully take advantage of this knowledge. Some essential questions requiring special attention for efficient burst transmission are (1) How long should nodes transmit in burst and how should this duration be determined? (2) How does burst transmission accommodate the co-existence of multiple communicating nodes? (3) How could the efficiency (in terms of channel utilisation, throughput, reliability, and energy, for example) of burst transmission can be guaranteed? These questions need to be carefully studied and addressed to determine the significance on network throughput, energy consumption and end-to-end packet delay.

Chapter 3

Background

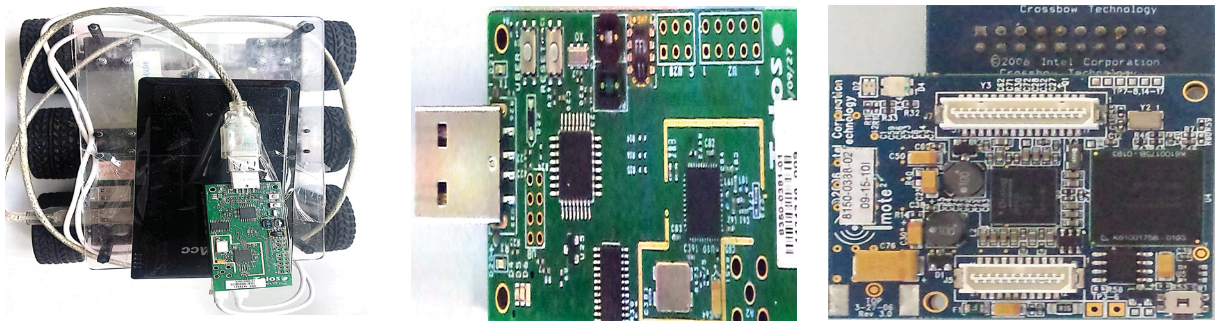
3.1 Empirical Study of Low-Power Wireless Links

The two methods widely adopted by the research community to study and evaluate network protocols are network simulations and testbed experiments. The most common network simulators for IEEE 802.15.4 are ns-3 [FR10], Cooja [JOFN$^+$09], OMNeT++ [AR08] and TOSSIM [PNMD03]. The advantage of using network simulators is the liberty to use variant operating systems, memory sizes, node mobility, scalability of network (large network with no additional cost) and provide support for complex link quality models (Rayleigh fading, Rician fading, Weibull fading etc.). However, network simulators have their own inherent inaccuracies and inabilities to capture real-world scenario. To overcome the limitations of network simulators, testbed experiments are becoming important. Some of the prominent publicly available testbeds are Motelab, Twist, Emulab, Kansei, Radiale, Senslab, Indriya and Flocklab[GPM05, VAAA06, JSF$^+$06, EAR$^+$06, BJd$^+$10, PGVJ12, MCL12, RFM$^+$13]. These testbeds are heterogeneous; support different hardware and software platforms. However, the drawback is their inability to emulate the reproducible mobility pattern. Mobilab [JZW17] overcomes this limitation by using programmable mobile robots in which the user can upload his or her own program image to specify a movement pattern of mobile nodes. Mobilab also integrates a traffic flow control management system (tfcp [WAD16]) to regulate the execution of repeated experiments.

Several research studies were carried out with different hardware platforms (TelosB, Micaz, Tmote, Imote etc.) to characterise the link quality of wireless sensor networks[MB01, NAH+10, ANT+10, AAV+10, GKW+02, LMH+03, GTSA04, LMD05, KPAP06, DBJ06]. These studies report that many link characteristics of low-power links are similar to those of traditional wireless networks such as mesh, ad-hoc and cellular networks. However, low-power links are highly dynamic and more prone to factors which affects the link quality. The reason for such behaviour is the low-cost, low-power communication hardware used in WSNs [KPAP10, LCHG07] which is shipped with low-gain antennas. However, these studies fall short of lack covering all aspects, such as the correlation of packet success and failure. They even sometimes contradict their own results which raises the need for performing extensive experiments in different environments, conditions and scenarios.

The efficiency of burst transmission protocols highly depend on the quality of the wireless link. The four main factors which leads to link unreliability are (i) environment factors which include path-loss, multi-path, and shadowing causing the degradation in the signal quality and increasing the background noise,(ii) hardware transceivers, low-power radio chips with low-gain antennas may distort the signal due to their internal noise and generate irregular radiation patterns,(iii) interference, caused by concurrent transmissions of IEEE 802.15.4 transceivers and cohabiting RF technologies working in the same 2.4 Ghz frequency band and (iv) mobility, which leads to the change in link quality as the direction of antenna, line-of-sight, and distance of the mobile node may change over period of time.

In order to investigate link quality fluctuation patterns and to identify the appropriate metrics that can describe the quality of the link, Mobilab was deployed in (i) different environments (indoor, outdoor), (ii) under different interferences (internal, external) (iii) and under mobility. Mobilab contains mobile robots, TelosB and IMote2 sensor nodes as shown in Figure 3.1. The testbed is fully implemented for the Tiny-OS, TelosB and Imote2 platform. Furthermore, Diddyborg robots are used for emulating different types of movement patterns (Random and Straight-line walk). Extensive experiments not only yields an understanding of the ways different factors affect quality, but also they help design efficient physical, MAC and routing layer protocols. These observations lay the foundation for design of the link quality estimation model for burst transmission presented in this thesis. RSSI, LQI, SNR, consecutive success (CS), consecutive failure (CF) and ARR are some of the basic metrics used in this dissertation to study the temporal characteristics of low-power WSNs.



(a) Robot Carrying Sensor Node (b) TelosB (c) IMote2

Figure 3.1: Hardware Platform

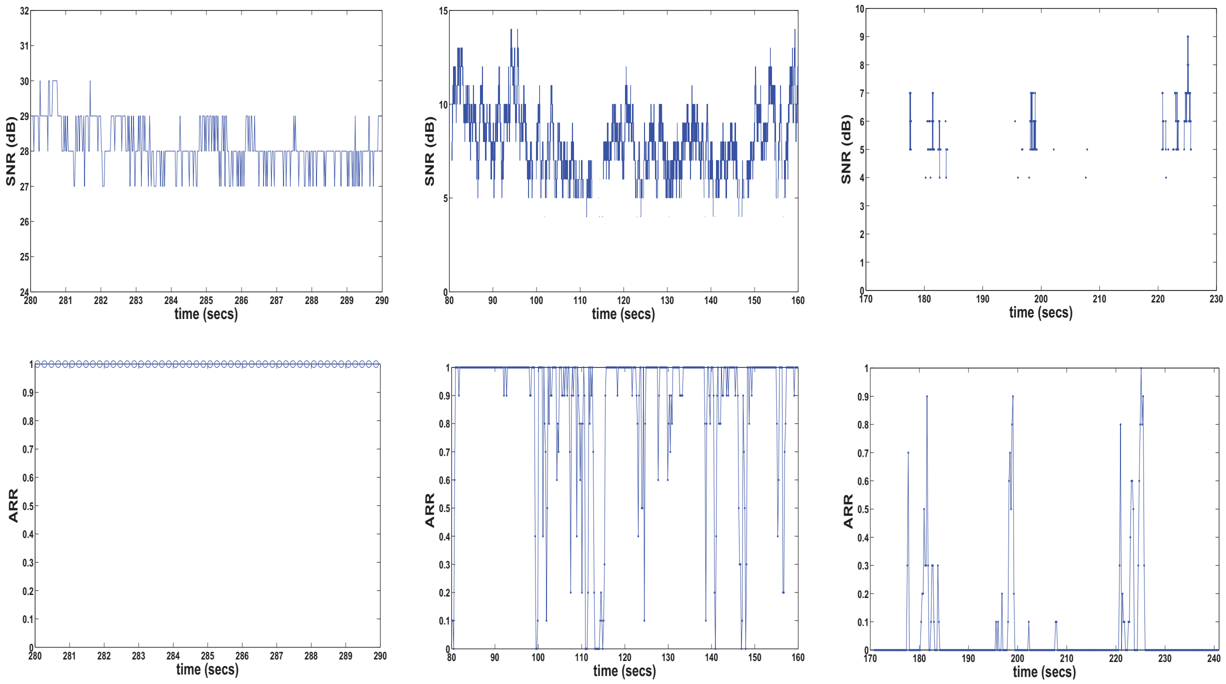
Table 3.1: Summary of the Experiment Set Up for Characterising the Fluctuation of Link Quality.

Location	indoor, outdoors
Successively transmitted packets	100000, 100,000
Overall transmitted packets	200,000
Inter-packet transmission interval	20 ms
Transmission power	-25,-15,-10,-7,-5 dBm
Speed	1.0-2.5 m/s
Packet size	28 Byte

3.2 Environment

To study link quality variance in different environments, different experiments were designed and conducted in both indoor and outdoor environments where packets were transmitted continuously. During these experiments different distances between a transmitter and a receiver as well as different transmission power levels were considered. Table. 7.1 summarises some of the parameters that are included in the experiment set up. Altogether more than 800,000 packets were transmitted. For management reasons, a 20 ms inter-packet interval (IPI) after each packet was inserted during the transmission of 800,000 packets. Each experiment was performed 10 times to remove radio irregularity.

For -7,-5, and 0 dBm transmission power, the distance was varied between the transmitter and the receiver in 2 m intervals from 1 m to 35 m, until the link was totally disconnected. For a -25,-15 and -10 dBm transmission power, the separation distance from 5 to 17 m in intervals of 2 and 5 m was used. None of the lost packet were retransmitted. A packet transmission was considered successful when the transmitter received an ACK packet. Otherwise it was marked as failed. From the successfully received ACK packets, the acknowledgment reception ratio (ARR) [KPAP10] was estimated. The ARR characterises the quality of a link and signal-to-noise



(a) Good link (b) Intermediate link (c) Bad link

Figure 3.2: An Illustration of the Three Link Types. In the good link $ARR \approx 1$ all the time. The intermediate link is characterised as $0.1 \leq \text{ARR} \leq 0.9$. In the bad link, ARR < 0.1. ARR $= 1$ meaning all packets were received successfully whereas $ARR \approx 0$ means nearly all packets were lost[WAD15].

ratio (SNR) characterises the quality of received packets. Hence through these experiments, a relationship between ARR and SNR was evaluated. Unlike the RSSI, the SNR contains information pertaining both the received signal's strength and the background noise.

Regardless of the environment, the location of the nodes and the distance separating them, packets were always received ($ARR \approx 1$) when the SNR was greater than 21 dBm. This link is characterise as a good link, consistent with previous observations made by other researchers. However, when the SNR was less than 2 dBm, the ARR was less than 0.1. Such parameters describe a bad link where 90% of the packets were lost. The region between the good and the bad links describes an intermediate region in which ARR varies uniformly between 0.1 and 0.9. The links in this region are bursty in nature. Figure. 3.2 displays the three regions identified to describe a bad, an intermediate, and a good quality link. The white spaces in the graph represent the packet loss.

(a) Indoor

(b) Outdoor

Figure 3.3: Experiments Performed in Different Environments

3.2.1 Indoor

The indoor experiments are conducted in three different locations: corridor, lobby, and cafeteria as shown in figure. 3.3 (a). In the corridor experiment, there are no obstacles between the sender and the receiver. In lobby experiments the sender and the receiver have fewer static obstructions. In the cafeteria, the experiment was performed during a busy hour where more than 100 people were present and acted as a moving obstruction between the sender and the receiver. The packets are transmitted in succession between the transmitter and the receiver in order to estimate link quality. The link quality was measured at the sender-side by retrieving data from the acknowledgment packet.

RSSI, LQI and ARR metrics are used to describe the fluctuation in link quality as shown in figure. 3.4. The window size is set to be 10 packets to calculate the ARR. For the corridor and lobby scenarios, as shown in figure. 3.4 (a) and (b), link quality is barely effected and observations suggest fewer packet losses over the period of time. The reason for this is the unobstructed line-of-sight communication and fewer to no obstacles between the transmitter and the receiver. On the other hand, in case of cafeteria deployment, the link quality deteriorates considerably and severe packet-losses are observed as shown in figure. 3.4 (c). The main reason for this is the blocking of the path between the sender and the receiver by human movements. Human body acts as an obstruction to the electromagnetic signal and degrades the signal quality resulting in poor link quality. A high transmission range was observed in indoor environments compared to outdoor environments for the same transmission power. For the transmitted power

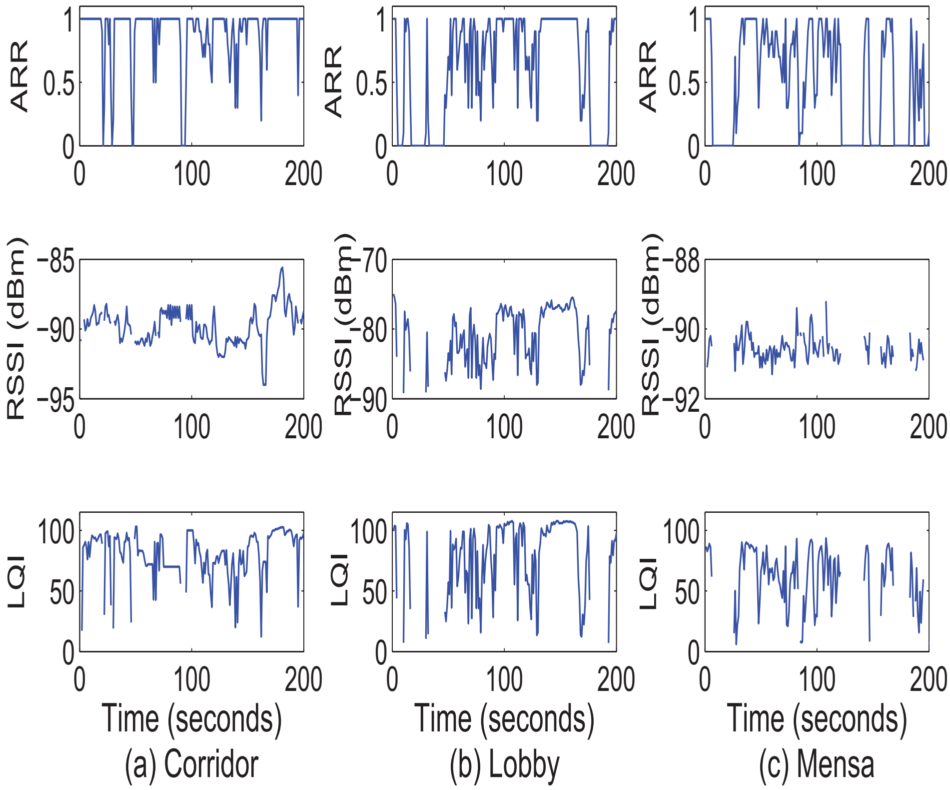


Figure 3.4: Link Quality Metrics Describing the Fluctuation of Links Between Two Static Nodes in Indoor Environments: (a) Corridor (b) Lobby (c) Cafeteria

ranging between -25 to -15 dBm, the packets were transmitted successfully between 14 to 27 meters respectively.

The outdoor experiments are performed in two different locations: the garden and the car parking-lot, as shown in figure. 3.3 (b). To make the comparison fair between indoor and outdoor experiments transmission parameters remain the same, depicted in table. 7.1. Figure. 3.5 shows the temporal variation in link quality using metrics ARR, RSSI and LQI in outdoor environments. The link quality detoriates to a greater degree in the parking-lot and has a high packet loss and a large transitional region as compared with the garden deployment. This is justified by the fact that parked cars obstruct the signals and cause the multi-paths which in turn results in signal quality distortion. Furthermore, the low-power wireless links outdoors can be affected by temperature, wind, grass-fields, trees, hills etc.

Hence it can be concluded that a change in the environment causes the frequency of link fluctuations to vary: in outdoor environment, large fluctuations were observed in signal quality, while an indoor environment brought small-to-moderate fluctuations. For a transmission power range between -25 to -15 dBm, the successful packet transmission range is in between 10 to 23

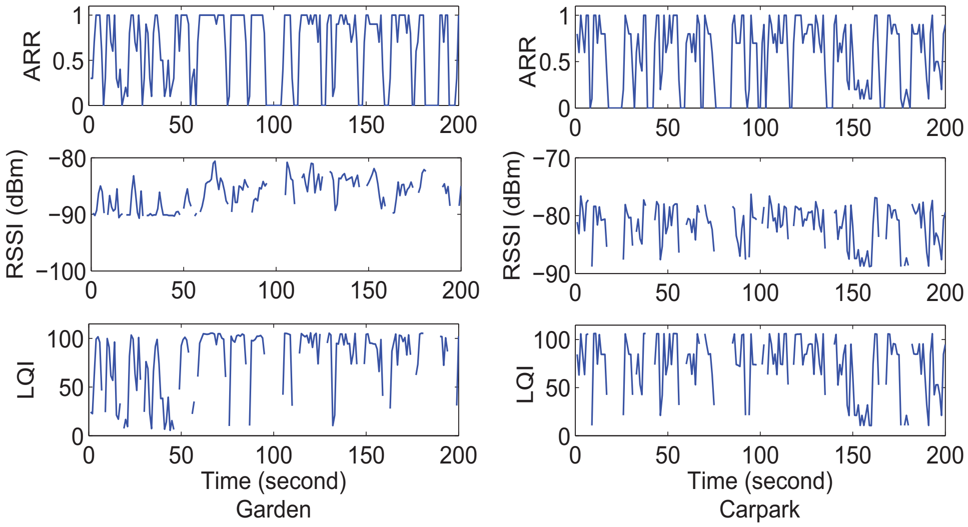


Figure 3.5: Link Quality Metrics Describing the Fluctuation of Links Between Two Static Nodes in Outdoor Environments: (a) Garden (b) Car Parking Lot

meters, respectively.

3.3 Interference

Interference is a phenomenon in wireless communication which occurs due to the RF spectrum sharing between transmitting nodes in an uncoordinated way. Interference highly affects communication availability and reliability. The problem of interference is becoming crucial for low-power WSNs due to the rapid emergence of heterogeneous wireless technologies over crowding the 2.4 GHz ISM band. In order to study the implications of internal and external interferers on a low-power IEEE 802.15.4 wireless network extensive experiments have been conducted.

3.3.1 Internal Interference

In order to characterise the effects of concurrent transmitters on the IEEE 802.15.4 wireless network, testbed experiments with simple network setup were conducted, as shown in figure. 3.6. The network consists of two pairs of transmitters and receivers in which one pair acts as an interferer. To vary the level of interference different levels of transmission power were set. A testbed setup was used in two communication scenarios: (a) **CCA-enabled**: the CC2420

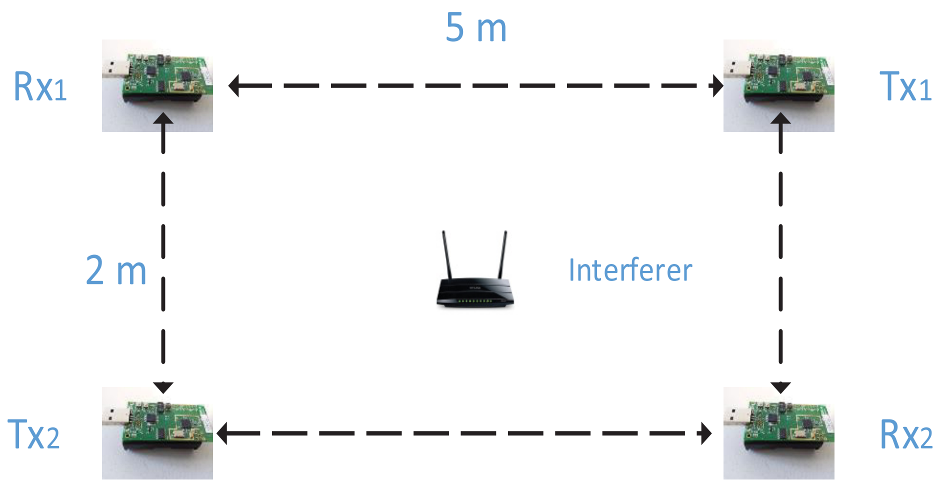
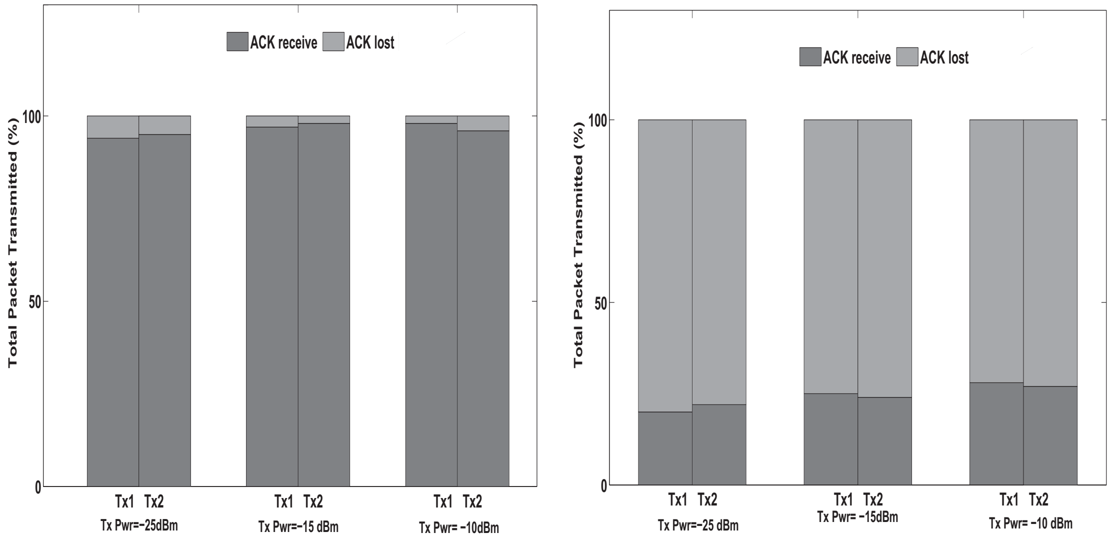


Figure 3.6: Testbed Setup to Measure Interference

radio employs a contention-based MAC protocol, based on the CSMA/CA technique to share the medium. When a node has a packet to transfer, it performs a clear channel assessment (CCA). If the channel is free the node transmits the packet immediately, otherwise it defers the transmission for a random period of time. (b) **CCA-disabled**: In this case the CCA is disabled or turn-off; therefore, the radio transceiver does not perform a clear channel assessment before transmitting each packet.

Figure. 3.7 summarises the percentage of packet loss for both scenarios. In the case of CCA-enabled the packet loss due to packet collision, packet loss is below 6% for different levels of interference. The packet loss is hardly effected by the level of interference due to the collision avoidance mechanism.

The throughput in bulk data transfer can be increased by dispensing with both CCA and random back-off before transmitting each packet. However, disabling CCA can be fatal to the radio link quality and packet success rate in the presence of another nearby transmitter. Figure. 3.7(b) shows the percentage of packet loss in CCA-disabled scenarios. The packet-loss is between (60-85%) on different links due to high collision rates. The level of interference and distance between the transmitters is directly proportional to the percentage of packet loss on each link. The outcomes suggest that the interference pattern can be helpful in designing an efficient transmission scheme.



(a) CCA-enabled (b) CCA-disabled

Figure 3.7: Percentage of Acknowledgment Loss for CCA-enabled and CCA-disabled Traffic Types.

3.3.2 External Interference

To study the impact of Cross Technology Interference (CTI) on burst transmission, two interferers, the Microwave Oven and the WiFi (IEEE802.11), are considered. These technologies differ in terms of transmission technique, power consumption, and data rates. However, they share the same ISM band as illustrated in figure. 3.8[AHS14]

An experiment using Siemens HF12M240, a residential microwave oven (MO), was performed in which a cup of water was heated to emulate the typical electromagnetic radiation. This radiation affects the communication of nearby sensor nodes which is in accordance with earlier findings [ATC+11, AHS14]. Figure. 3.9(a) shows the fluctuation in link quality metrics of transmitting nodes in the presence of microwave radiation. A small number of consecutive losses(8-10 packet) were observed. Occasionally the number became larger. Also the packet loss was found to be periodic. This is justified as the microwave oven generates a periodic interference of shorter duration (5ms). Different transmission powers between the sender and the receiver are used, for the same distance between microwave and the transceivers. Observations revealed a considerable reduction in packet loss at higher power levels, upto 30% reduction in packet loss.

IEEE 802.11 is the most predominant wireless technology in indoor environments. To generate interference, the TP-Link TL-WR841N router (access point) and a smartphone (client) that

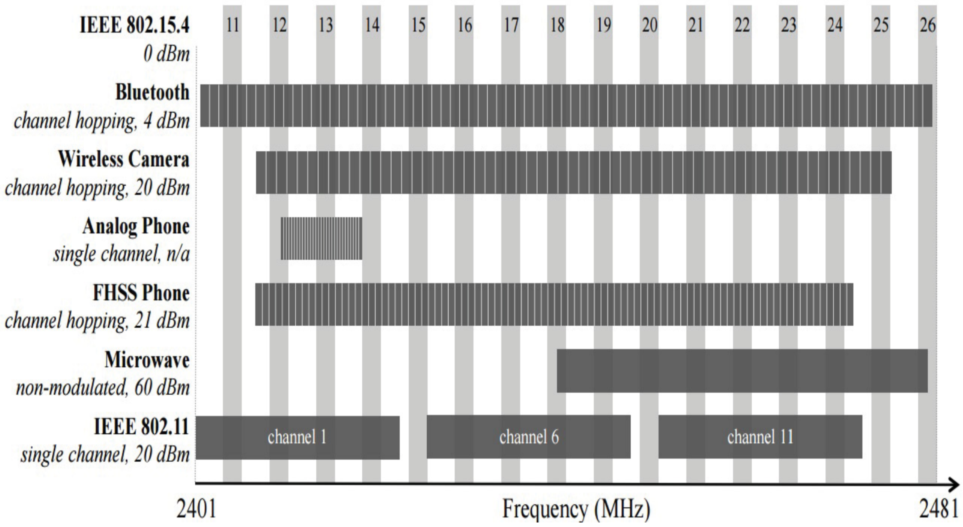


Figure 3.8: IEEE 802.15.4 Channels with RF Interferers in the 2.4 GHz ISM Band [AHS14]

supports IEEE 802.11 b/g/n in the 2.4GHz ISM band was used. In my experiments the client transfers the file through an access point to the remote location. The router is configured to use channel 11 and TelosB sensor nodes uses channel 24 which overlaps with WiFi channel 11. Figure. 3.9(b) shows the packet loss in the presence of the WiFi interferer. The packet loss is between 40-75 %. This can be attributed to the highest transmitting power used by the WiFi which produced irregular interference patterns, resulting in significant consecutive packet losses. Hence, when using WiFi, increasing transmission power will not improve the packet success rate.

3.4 Mobility

In MWSNs, the link quality fluctuates more rapidly as compared with static deployment due to a change in environment, path loss, fading, doppler effect, and shadowing. To observe the effects of mobility, during my experiments, a human holds a sender node and performs different walk models in a predefined area as shown in figure. 3.10. The sender node transmits packets in burst to the receiver while moving at a constant speed. It stores the data of the acknowledgment packets. To explore the impact of sensor node movement on link quality, the experiment was performed by walking at slow, medium and fast speeds.

Figures. 3.11 (a) and (b) show the link quality fluctuations in a mobile scenario. It is evident from the link quality metrics, ARR, RSSI, and LQI, that in a mobile scenario, the percentage

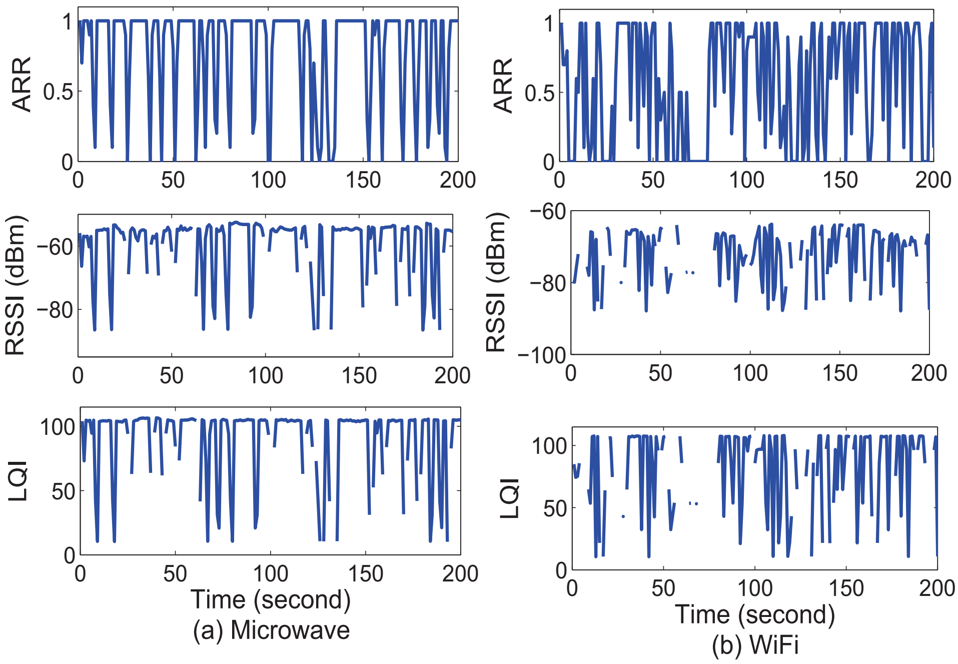


Figure 3.9: Link Quality Metrics Describing the Fluctuation of Links Between Two Static Node in the Presence of External Interferers (a) Microwave (b) WiFi

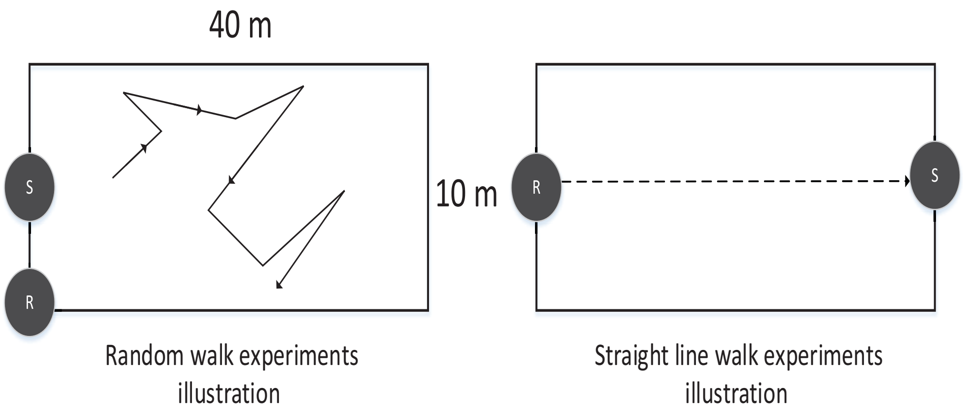


Figure 3.10: Mobility Pattern of a Mobile Node

of intermediate links is higher than the static scenario as transmission success rate fluctuates strongly over a short period of time. It is also evident that the speed of the movement of the mobile node also disturbs the link quality. At higher speeds, the packet loss increases . This leads to the conclusion that in order to model link quality estimation in a mobile scenario, an estimator needs to deal with short-term link quality fluctuation in real time.

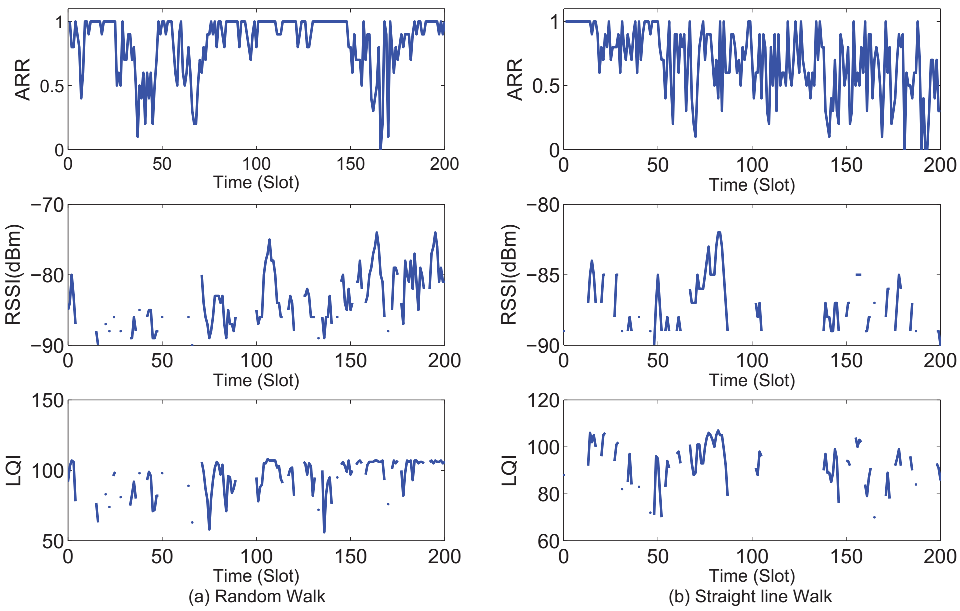


Figure 3.11: Link Quality Metrics Describe the Fluctuation of Links Between a Static Node and a Mobile Node (a) Moving in a Random Walk and (b) Moving in a Straight Line

3.5 Summary

The basic methodology used to understand the behaviour of any process in general, and the performance of a wireless channel in particular, is running experiments in a real-world testbed. Researchers opt for testbed experiments to study the behaviour of wireless links and validation of their protocols. To understand and evaluate the performance of wireless link, extensive experiments are conducted by using Mobilab. The main goal of this empirical study is to scrutinise the effects on the quality of wireless link by such factors as the environment, interference, and mobility. The study further aims to establish a correlation between packet success and failure. The findings of the study are summarised below:

Environment

Observation 1: The link quality highly depends on the deployment environment. Links in indoor environments perform better than links in outdoor environments. The packet loss rate was higher for the same link (same transmission parameters and distance between the sender and the receiver) outdoors as compared with indoors.

Observation 2: Link quality has some degree of correlation with distance and transmission power, but it is not a linear relationship. A decrease in the ARR is observed as the distance between transceivers increases, regardless of the level of transmission power. However, in the transitional region these two parameters had no correlation between them as reported by earlier studies [NAL+12]. From the results of the experiment, we can deduce that at different transmitter power levels, -25, -15 and -10 dBm, the connected regions were observed to be at 9, 17, and 40 m respectively, in an indoor environment and 7, 13, and 30 m respectively, in an outdoor environment. Hence, this experiments proves that the quality of the radio signal degrades as the distance between the sender and the receiver increases.

Observation 3: The percentage of intermediate quality links is higher in an outdoor environment as compared to an indoor environment. It was observed that the quality of the signal deteriorates faster in outdoors compared with indoors as transmission range for -25 dBm is 16 m indoors and 13 m an outdoors.

Observation 4: Another observation shows that the human body can obstruct the communication path and degrade the link quality considerably. Also of note is how the change in antenna direction can affect the link quality.

Interference

Observation 1: Link quality is highly affected by the presence of internal and external interferers. The internal interference can be mitigated to a certain level by enabling a clear channel assessment and a random back-off. In case it is CCA-enabled, the packet loss is about 1-6%; in absence of the CCA, the packet loss increases upto 85%.

Observation 2: Cross technology interference such as microwave and WiFi interference affects the signal quality considerably. Microwave ovens generate periodic interference of smaller periods which is evident from the small size of the consecutive packet losses (8-10 packets) measured during experiments. Burst transmission schemes can take advantage of this periodicity to model link quality fluctuation by using long-term characteristics of the link.

Observation 3: WiFi on the other hand is aggressive interferer which use a transmission power 100 times higher than that of the IEEE 802.15.4, resulting in high packet losses. The packet loss reach upto 80% with irregular patterns, unlike with the microwave. Hence, short-term fluctuation can be modelled by online link quality estimators for efficient burst transmission schemes.

Mobility

Observation 1: The mobility of the sensor node introduces high disturbances in link quality and affects the performance of bulk/burst transmission protocols.

Observation 2: Each mobility pattern has different degree of effects on the quality of wireless links. The experiment using the straight-line walk model revealed long-to-middle term link quality fluctuations, whereas random walk models have short-term link quality fluctuations.

Observation 3. As the mobile sender moves away from the receiver the link quality deteriorates over a period of time. An observation was made that the ARR parameter starts to drop below 70% as the mobile node moves 3m away from the receiver at transmitting power of -25dBm.

Observation 4. Mobility increases the size of the transitional region in wireless sensor networks. Furthermore, the speed of the mobile node also affects the size of the transitional region.

Chapter 4

An Offline Link Quality Estimation Model for WSN

4.1 Motivation

Link quality fluctuation affects the performance of applications in wireless sensor networks. In some applications, wireless sensor networks are deployed on the objects or embedded into the processes they monitor, which considerably influences the quality of communication between nodes [WC10]. For example, in structural health monitoring it is the oscillation of a bridge, in water quality monitoring, the water and the movement of water, in healthcare applications it is the movement of people, and in precision agriculture it is the movement and the shadow of plants that affect the quality of an established link. Fluctuation of link quality in turn has a negative impact on success of packet delivery for applications which require high throughput and for most normal relay nodes which should aggregate and forward packets towards a base station. Furthermore, the repeated retransmission of lost packets increases not only latency at all levels of communication but also energy consumption, which may reduce the lifetime of the entire network.

Since data communication consume most of the energy, having efficient transmission by taking channel conditions into account is critical to prolong the lifetime of wireless sensor networks. Several factors affect the link quality. These include fading, shadowing, multipath and time-varying multi-user interference. The IEEE 80215.4 transceiver contain radio chips, such as

CC1000, CC2420, and CC2500. They provide a summary of link quality metrics (RSSI, Noise and LQI) by evaluating incoming packets. This information is then forwarded to the higher-layer protocols such as the MAC layer and the routing layer. This knowledge can be useful in several ways. For example,

- MAC layer protocols can optimise their duty cycle to save energy consumption.
- Link quality estimators use this information to calculate the number of packets necessary to retransmit and decide whether retransmission will be fruitful.
- MAC layer protocols decide to transmit packets in burst or packet-by-packet.
- Routing protocols select the best possible route to the destination and choose the neighbours to forward the next packet .
- For burst communication, the knowledge of link quality helps to determine the optimal burst size.

Link quality in wireless sensor networks cannot be known in a deterministic sense given that the fluctuation of link quality varies over a period of time and has a randomness which should be modelled as a random process. To model a random process statistics pertaining to link quality metrics can be obtain directly from the received data packets. For some applications such as structural health monitoring, agriculture monitoring, railway and volcano monitoring, wireless sensor networks are deployed for a long period of time. Hence, sufficient statistics of link quality metrics can be collected from the acknowledgement packets. Finding the periodicity in packet successes and failures by using the collected statistics will enable applications to decide for how long they will transmit packets consecutively and for how long they will refrain from transmitting. However, it does not possible to define the periodicity in link quality in strict sense because the factors on which link quality depends are very diverse and uncontrollable. Instead, periodicity can be defined in mean square sense [WAD15]:

The mean square periodicity for a random process, $\mathbf{l}(\mathrm{t})$, can be defined as [PU02]:

$$E\left\{ \left(\mathbf{l}(t+T)-\mathbf{l}(t)\right)^2 \right\} = 0 \tag{4.1}$$

where T is the period. The auto-correlation of such a process must be doubly periodic:

$$R(t_1 + mT, t_2 + nT) = R(t_1, t_2) \tag{4.2}$$

where t_1 and t_2 are two arbitrary time instances and m and n are two arbitrary integers. It should be noted that periodicity in the mean square sense does not require the process to be strictly periodic with period T and a probability of 1.

To determine both the auto-correlation function R and the time period T together is a difficult process. However, if the process **l**(t) can be considered stationary in a wide-sense, then it is possible to obtain the distribution or density function by observing link quality statistics over a certain period of time. From the distribution function it is possible to determine T. This chapter will discuss and propose two lightweight approaches to determine the periodicity in link quality fluctuation and compute the number of packets necessary to transmit in burst as well as number of packets to halt as to avoid a bad link quality period. The first is CPB model [WAD15] which uses conditional distribution functions of consecutive success and failure conditioned on the SNR threshold. The second is the DMB model [ZJDW15a] which uses k-mean clustering and a double discrete Markov model to determine the correct burst size [ZJDW15b].

Estimating link quality fluctuation and link burstiness by deferring packet transmission has been proposed in the past. In contrast, to the best of our knowledge we are the first to model the periodicity of packet successes and failures and use this knowledge to compute the optimal burst size. This approach takes advantage of channel periodicity to schedule packet transmission in good channel conditions and refrain from transmitting packets during poor channel conditions.

4.2 Link Quality Metrics

Most existing, off-the-shelf transceivers provide the basic link quality metrics including RSSI, LQI, and background noise level. Unfortunately, it is not possible to establish deterministic relationships between these metrics and successful packet delivery. Packets can be successfully transmitted with a certain probability even when the metrics indicate that the link is bad. In

Table 4.1: A summary of Physical Parameters Used to Establish the Links.

	link1	link2	link3	link4	link5
distance (m)	8	19	35	27	23
power (dBm)	-3	-3	-15	-15	-15
location	Indoor	Indoor	Outdoor	Outdoor	Outdoor
IPI (ms)	20	20	20	20	20

fact, packets can be lost even if the metrics indicate that the link is good. Srinivasan et al. [KPAP10] introduce a metric called the acknowledgement reception ratio (ARR) to summarise the relationship between successful packet delivery and the signal-to-noise ratio (SNR). We selected the ARR to characterise the link quality and the SNR to charaterise the quality of the individual packet. Unlike the RSSI, the SNR contains information relevant to the signal strength of the received packet and the background noise. The ARR metric is computed as follows: first, a sequence of packets are divided into a set of sub-sequence. Each sub-sequence is transmitted in succession and each packet in a sub-sequence is acknowledged when it is successfully received. Then for that sub-sequence, the ARR is the ratio of the number of successfully received acknowledgement packets to the total number of transmitted packets. The SNR of that sub-sequence is the average of the successfully received ACK packets. Likewise, once the entire set of sub-sequences is transmitted, the ARR is produced for each sub-sequence, and the corresponding SNR is computed. Then a 2-dimensional graph of the ARR vs. the SNR is plotted to summarise the relationship between the two quantities. The merit of this approach is that the quality of a link can be evaluated independent of the distance of separation between the transmitter and the receiver and physical layer parameters such as the transmission power and the specific channel allocated. The weakness of this approach is that for a short duration, the channel's characteristic is assumed to be both symmetrical and correlated to account for the SNR of lost packets. We adopt this approach to evaluate the effect of link quality fluctuation upon successful packet delivery[WAD15].

Table 4.1 summarises the links selected and the transmission parameters for each link used for the experimental study. It also evaluates the proposed scheme in this chapter. Figure. 4.1 displays the relationship between the ARR and the SNR for link 5 in our experiment. As can be seen in the figure, packets are successfully delivered with higher probabilities when the SNR is large (for an SNR greater than 7 dB, the probability approaches unity). However, one can also observe the existence of successful packet delivery even when the SNR is below 1 dB. If

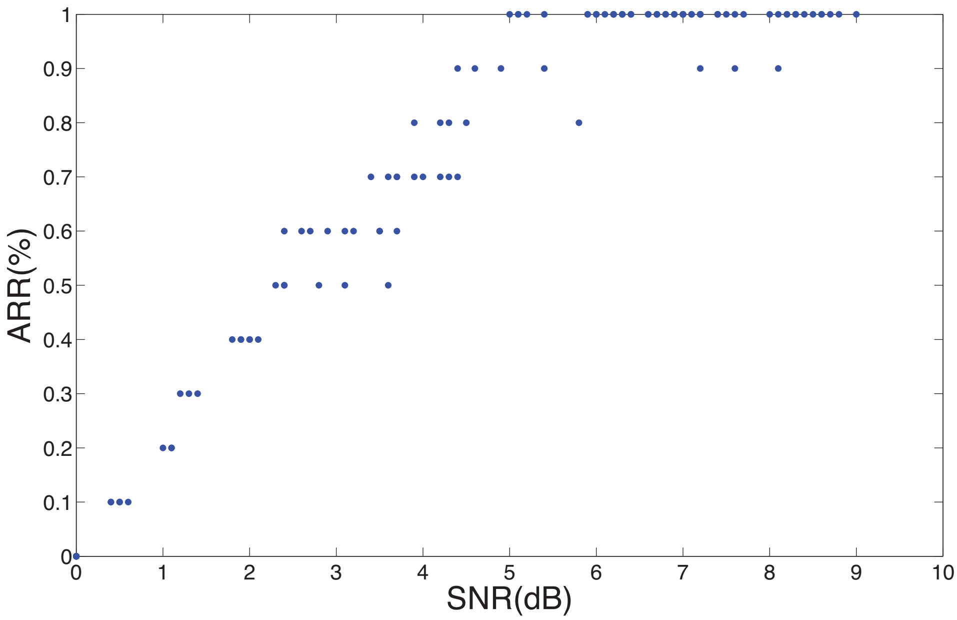


Figure 4.1: A Summary of the Relationship Between the SNR and the ARR of a Wireless Link. SNR is Computed as the Difference Between the RSSI and the Background Noise Power.

(1) the probability distribution function of the SNR of incoming acknowledgement packets and (2) the duration for which a link can be considered stable for a given SNR can be estimated, then it is possible to determine with what probability outgoing packets can be delivered or lost. This knowledge is useful in many ways. For example, if a node can determine that a link will be "bad" for the next τ seconds, then it can refrain from transmitting packets and sleep during this time. This not only saves energy but also frees the channel for those nodes possessing an acceptable link quality[WAD15].

4.3 Link Quality Estimation Model (I)

This section determines the appropriate size of a burst by employing a conditional cumulative distribution function (CDF) of consecutive successes and consecutive failures. The distribution function is obtained by conditioning the SNR threshold using incoming acknowledgement packets. The value of the SNR threshold defines the reliability of a link and is to be chosen by the individual application. The higher the SNR threshold the higher the reliability of the packet delivery. However, as the value of the SNR threshold increases the packet delay will also increase. The expected value of the CDF describes the stable duration, i.e., all packets transmitted within this duration most likely experience a similar link quality. Based on this information the MAC layer can decide for how long it needs to stay in transmit mode to transmit packets and how long the duration of a bad link quality lasts so that it can switch off the radio to conserve energy consumption[WAD15].

4.3.1 Theoretical Conditional CDF

Consider the fluctuation in the signal-to-noise ratio of the received ACK packets for a particular link as a random variable **s**. The CDF of a random variable **s** can thus be described as $F(s) = P\{\mathbf{s} \leq s\}$, where s is a real number. The distribution function is obtained after setting a SNR threshold on a random variable function. Equation 4.3 define a conditional CDF of the duration in which the link can be considered stable[WAD15] [1].

$$F\left(\tau|s_{th}\right) = P\left\{\mathbf{T} \leq \tau|\mathbf{s} \geq s_{th}\right\} \tag{4.3}$$

where **T** is a stable link duration expressed as a random variable, because it cannot be known in a deterministic sense. Equation 4.3 can also be expressed as:

$$F(\tau|s_{th}) = \frac{P(\mathbf{T} \leq \tau, \mathbf{s} \geq s_{th})}{P(\mathbf{s} \geq s_{th})} \tag{4.4}$$

$$F(\tau|s_{th}) = \frac{P(\mathbf{s} \geq s_{th}|\mathbf{T} \leq \tau)F(\tau)}{P(\mathbf{s} \geq s_{th})} \tag{4.5}$$

$$F(\tau|s_{th}) = \frac{P(\mathbf{s} \geq s_{th}|\mathbf{T} \leq \tau)F(\tau)}{1 - F(s_{th})} \tag{4.6}$$

The expected duration in which the link quality is above the specified threshold can be expressed as:

$$E\left[\mathbf{T}|s_{th}\right] = \int_{0}^{\infty} \left[1 - F\left(\tau|s_{th}\right)\right] d\tau \tag{4.7}$$

[1] It should be noted that stable does not imply good. It simply mean that the quality of the link in this duration is considered unchanging.

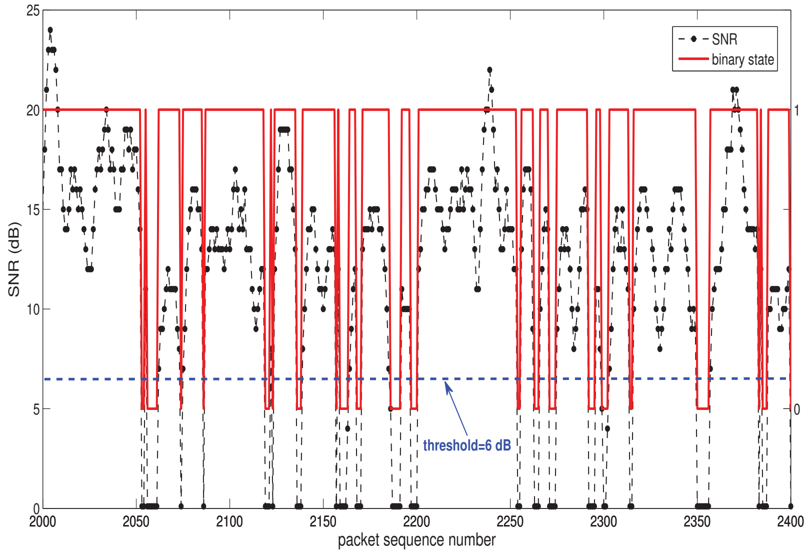


Figure 4.2: The Fluctuation of the SNR in the Received ACK Packets and the Transformation of the Continuous Function is Used to a Discrete Function to Estimate the Conditional Duration of a Stable Condition.

The total number of packets which can be transmitted consecutively or the number of packets which can be halted before transmitting again is determined by taking equation 4.7 along with the packet size (the default packet size is 28 Bytes in a TinyOS environment), the transceiver's data rate (250 Kbps for CC2420), and the MAC protocol primitives such as the clear channel assessment and random back-off (C&B) into consideration[WAD15].

4.3.2 Empirical Conditional CDF

The stable duration of each link under consideration can be determined empirically by using equation 4.7. Let us consider an example to understand the approach. First, a random function of the SNR fluctuation of received ACK is obtained from the experimental data as shown in figure. 4.2. Next, to define a stable duration a continuous function of the SNR fluctuation is transformed into a discrete function by setting a SNR threshold. According to the IEEE 802.15.4 specification, a typical low-cost detector implementation requires a minimum SNR value of 5-6 dB to achieve a packet error rate (PER) of 1%. However, my empirical study reveals that most of the intermediate quality links have SNR ranges between 5 to 21 dB. Therefore, a higher value of $SNR > 10\ dB$ is also considered[WAD15].

Figure. 4.2 shows the fluctuation of the SNR of the received acknowledgement packets and the transformation of the continuous function into a discrete function by setting the SNR threshold in an outdoor location. The sender nodes transmit 30,000 packets continuously to the receiver. Lost packets were not retransmitted. The distance between the transmitter and the receiver is 5m and the transmission power of both nodes is -10 dBm. The value of the SNR threshold is 6 dB and described as follow:

$$f(t) = \begin{cases} 1 & \text{if SNR} \geq 6\ dB \\ 0 & \text{otherwise} \end{cases} \tag{4.8}$$

By setting different SNR thresholds a continuous function has been changed into a discrete function. The discrete function is a function of time since packets are transmitted consecutively. The width of each pulse in a discrete function can be understood as a time duration and defined as a stable duration. All the packets transmitted in these duration are either lost or successful each having the same probability. Then, the width of each pulse above the SNR threshold is measured to obtain the conditional distribution function of the time duration for those packets which were successfully transmitted in succession as given by equation 4.6. Similarly, the width of each pulse below the SNR threshold is measured to obtain the conditional CDF of the time duration for losing transmitting packets in succession. Figure. 4.3 shows the CDFs of continuous success and continuous failure for SNR threshold of 6 dB. Figure. 4.4 display the CDFs of consecutive successes and consecutive failures for different values of the SNR threshold. The value of the SNR threshold determines the reliability of packet transmission and must be chosen by each individual application depending on its requirements. For example, if the application requires a high packet success rate and a low packet loss rate, a higher value of the SNR threshold should be set. However, if the application can tolerate link losses and needs a low transmission delay then it should select the low SNR threshold value. Figure. 4.5 compares the CDF of continuous success for different links with the same SNR threshold[WAD15].

4.4 Link Quality Estimation Model (II)

The above listed approach is limited by its use of a conditional distribution function obtained by empirically defining SNR thresholds, given that this function may not be applicable for different

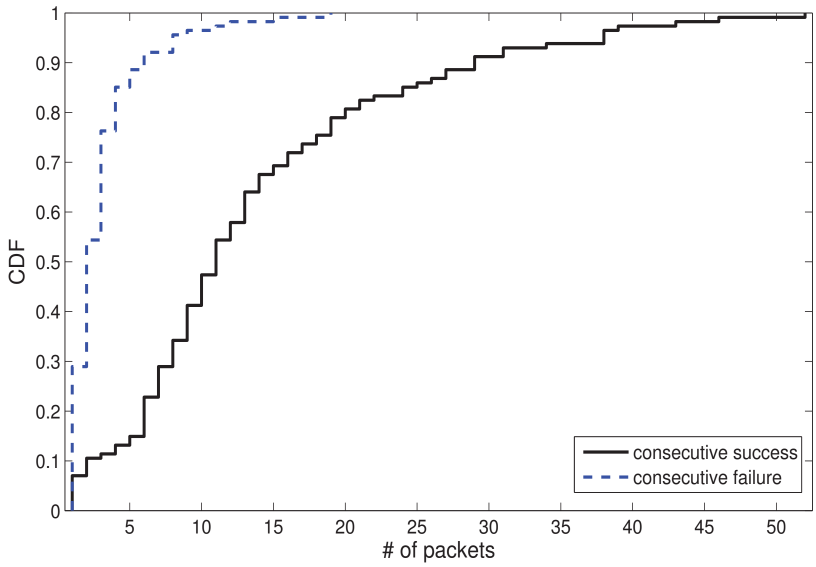


Figure 4.3: The Empirical Conditional Distribution Function of Consecutive Successes and Failures of a Link.

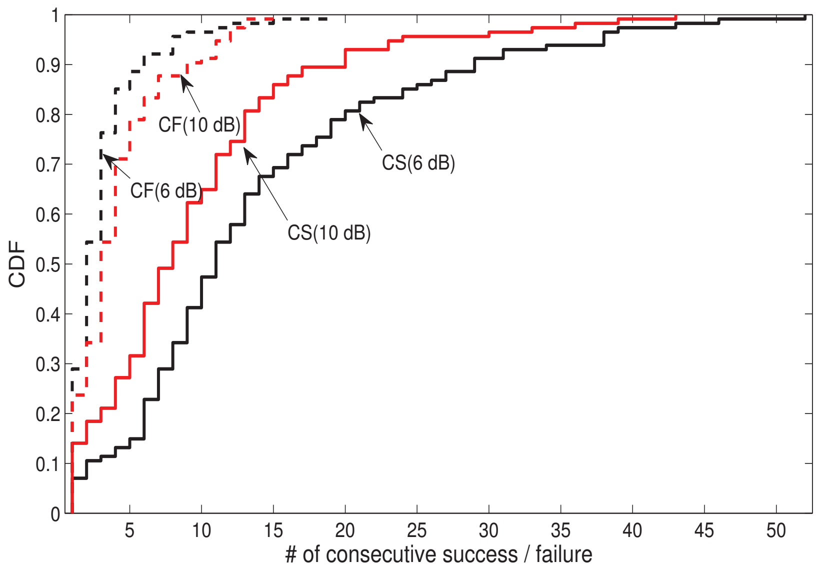


Figure 4.4: The Empirical Conditional CDF of Consecutive Success (CS) and Consecutive Failure (CF) for different SNR Thresholds.

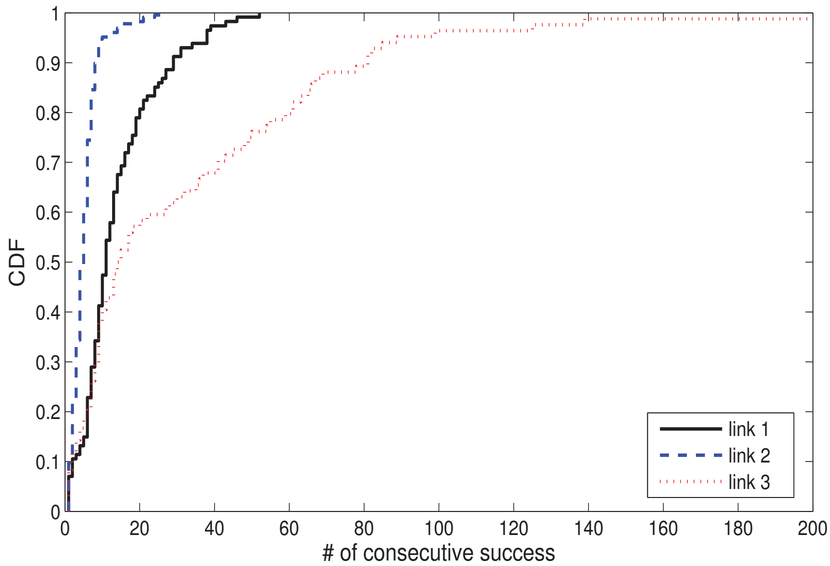


Figure 4.5: The Conditional CDF of Consecutive Success for Different Links.

types of links. In order to overcome this limitation, I propose using a machine learning technique called Discrete Markov Model along with a data clustering algorithm. The model first classifies link quality into different clusters (or states) and determines the transition probability between the states. Then, it estimates the average duration of a link staying in a state and the optimal number of packets that can be transmitted in this state.

4.4.1 Clustering

In most practical settings, the quality of a link does not stay at a certain level for long; instead, it fluctuates between different levels. For tractability, these levels can be categorised into a few countable and non-overlapping regions. The average ARR of these regions can be considered to characterise link quality. Previously, various researchers have classified these regions into good ($ARR \approx 1$), intermediate ($0.9 \leq ARR \leq 0.1$) and poor ($ARR < 0.1$) states [HOL$^+$09, SAAP08, TP09b]. However, a strict classification of link quality into fixed regions is not realistic, because physical links have individual aspects. Unlike previous approaches, k-mean clustering is use to determine the optimal number of clusters that best describe the distinct states of a link. The k-mean clustering algorithm can be realised in two steps[Mac02]:

1. **Assignment step:** In assignment steps the algorithm randomly selects 'k' number of clusters, after which a center for each cluster is calculated. The Euclidean distance is cal-

culated between each data point and the cluster center. Mathematically, the assignment step is given as follows [Har75]:

$$S_i^{(t)} = \Big\{x_p : ||x_p - m_i^{(t)}||^2 \leq: ||x_p - m_j^{(t)}||^2 \forall_j, 1 \leq j \leq k\Big\} \tag{4.9}$$

where, 'x_p' stands for the data points, 'm_i' is the cluster center of cluster 'i' and S_i denotes the cluster 'i'

2. **Update step:** In the update step observation points are reassigned to corresponding clusters whose distance is minimum to the cluster center. Then, a new cluster center is calculated using equation 4.10. Once the assignment of data points is no longer possible the algorithm stops[Har75].

$$m_i^{(t+1)} = \frac{1}{|S_i^{(t)}|} \sum_{x_j \epsilon S_i^{(t)}} x_j \tag{4.10}$$

For $n >> 1$, let A_n be a discrete sequence of successfully acknowledged and lost packets from which the 2-dimensional ARR vs. the SNR vector can be produced. The k-mean clustering algorithm [S.06] can be applied to this vector with the goal of partitioning it into k mutually independent clusters, each cluster with its centroid representing a link quality state. The k-mean treats each value of the ratio (ARR, SNR) pair as an object. Hence, similar objects are located close to each other, thus forming a cluster. To determine the optimal number of clusters for a given link, we employed the *silhouette method* [P87], which is an iterative method based on the comparison of the average distance between points within a cluster and across clusters. the goal is to determine the number of clusters which can distinctly categorise a dataset. We begin with 2 clusters and increase the number of clusters until we obtain an optimal measure of distinctness, i.e., the maximum silhouette value, s(i), which is calculated as[P87]:

$$s(i) = \frac{b(i) - a(i)}{max[a(i), b(i)]} \tag{4.11}$$

where $a(i)$ is the average distance from the i_{th} point to all the other points in the same cluster and $b(i)$ is the minimum average distance from the i_{th} point to all of the points of the different clusters (see Figure 4.7). Figure 4.6 displays the centroids of three clusters computed by the silhouette method for link 5.

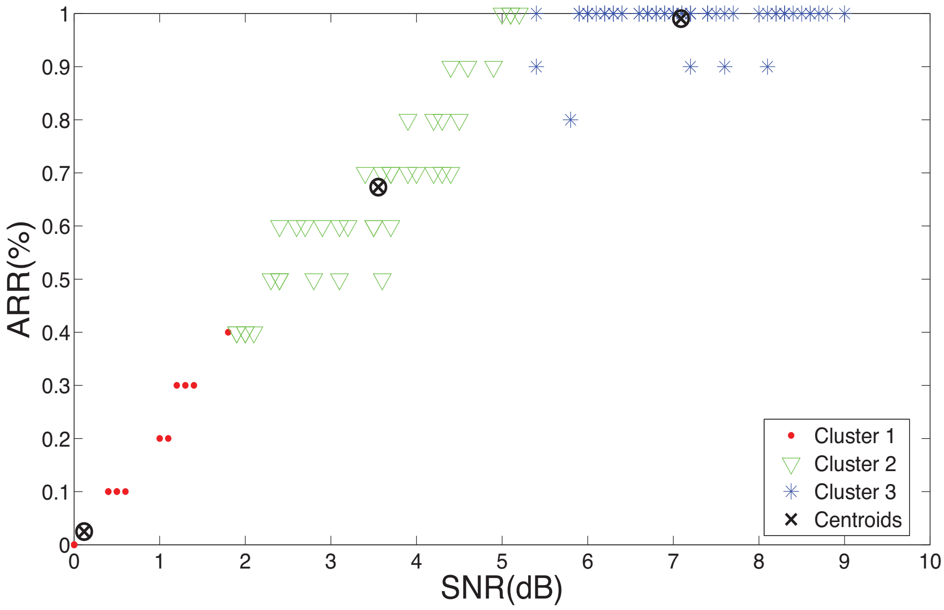


Figure 4.6: SNR vs. ARR Characteristics after Clustering.

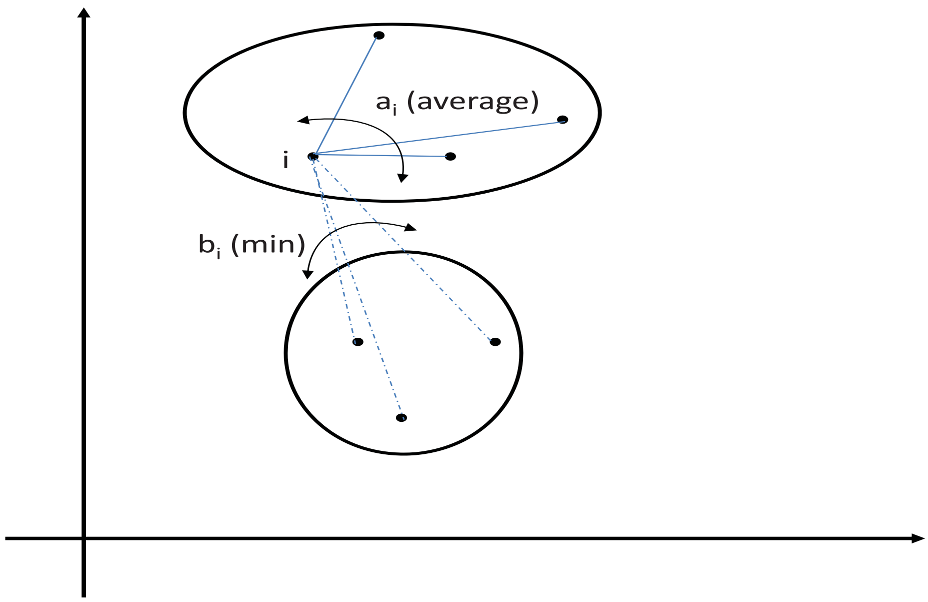


Figure 4.7: The Silhouette Method Used to Compute the Maximum Number of Clusters that can Distinctly Categorise a Dataset.

4.4.2 State Transitional Probabilities

After clustering, the next step is determining the probability of transitions between the clusters (signifying link quality fluctuation) during a continuous transmission of packets. This can be done using a first order Markov chain [R89]. In this approach, time is divided into discrete slots and packets are transmitted in burst in each slot (for our case, the burst size is set to be 10 packets). Using the acknowledgement packets in each slot, the ARR, the average SNR, and the link quality state (cluster) are determined as discussed in section 4.4.1. After a sufficiently large number of packets are transmitted and the ARR, the SNR, and link quality state of subsequent slots are estimated, the fluctuation in link quality is described by a state transition probability, which is computed as follows[R89]:

$$a_{ij} = P\left(S_j|S_i\right) = \frac{N_{i\to j}}{\sum_{m=1}^{M} N_{i\to m}} \tag{4.12}$$

where M is the total number of states and N is the number of transitions. An interesting aspect of equation 4.12 is the possibility of asking (and answering) the following question: given that the channel is in a known state during the beginning of slot τ, what is the probability that it stays in the same state for the next d slots (as expressed by equation 4.13[R89]). This is an important question because it directly addresses the problem of link stability[R89].

$$o = \left\{ \begin{matrix} S_n, & S_n, & S_n & \multirow{2}{*}{.....} & S_n, & S_m & \multirow{2}{*}{$\neq S_n$} \\ 1 & 2 & 3 & & d & d+1 & \end{matrix} \right\} \tag{4.13}$$

The question can be answered using the following expression:

$$P_n\left(d\right) = \left(a_{nn}\right)^d \left(1 - a_{nn}\right) \tag{4.14}$$

Where a_{nn} is the probability that the link quality is in state n and remains in the same state in the next time slot. Note that the plot of $P_n(d)$ for all d gives the probability mass function for state n, from which it is possible to determine the expected number of slots for which the link quality will stay in state n [R89]:

$$\bar{d_n} = \sum_{d=1}^{\infty} dP_n\left(d\right) = \frac{1}{1 - a_{nn}} \tag{4.15}$$

4.4.3 Slot Scheduling

Long-term link quality fluctuation can be estimated using equations 4.12 and 4.15. In the beginning c packets are transmitted in burst (for our case, we set $n = 10$) and based on the ARR of that slot, the state of the link quality is estimated. Then using equation 4.15, the

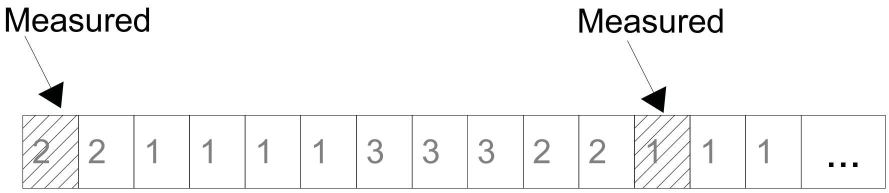


Figure 4.8: Slot Scheduling

expected number of slots in which the link quality remains in the same state is estimated. Once the expected number of slots are used, the next state is estimated using equation 4.12 and then the same process is repeated all over again. This approach however has two limitations. First, since the transition between states is a probabilistic term, the approach will always choose the transition with the highest probability. However, a state transition with a low probability does not mean that the transition will not occur. Second, once a wrong transition is chosen, the subsequent $\bar{d_n}$ slots computed using the equation 4.15 for that state do not reflect the actual link quality state. To deal with these problems we introduced two correction factors. First, to correct the error that occurs due to wrong transitions, the transmission scheme takes periodic measurements and estimates the channel states. If there is a discrepancy between the latest estimated state and the state determined by the transition probability, then the latest state is taken as the present channel state (this approach is illustrated by Figure 4.8). Figure 4.9 illustrates the ratio of successfully received to transmitted packets for difference values of M, where M is the distance between time slots in which measurement is taken to correct state transition. Understandably, as the distance increases, transition error increases and packets are successfully transmitted with a small probability. Second, to enable transition into states with low transition probabilities, the transitions are randomised as follows: $randomselect\,(S, A)$, where $S = (S_j, S_k, ..., S_n)$ and $A = (a_{ij}, a_{ik}, ..., a_{in})$.

4.4.4 Burst Size Determination

After the state sequence is determined, the next step is determining the number of packets that should be transmitted in burst in each state. The goal is to minimise the number of lost packets. Once again a first order Markov chain is employed for this step, but this time, the number of states is fixed to two, success (1) and failure (0). The sequence of received acknowledgement packets during a test phase is used to determine the state transition proba-

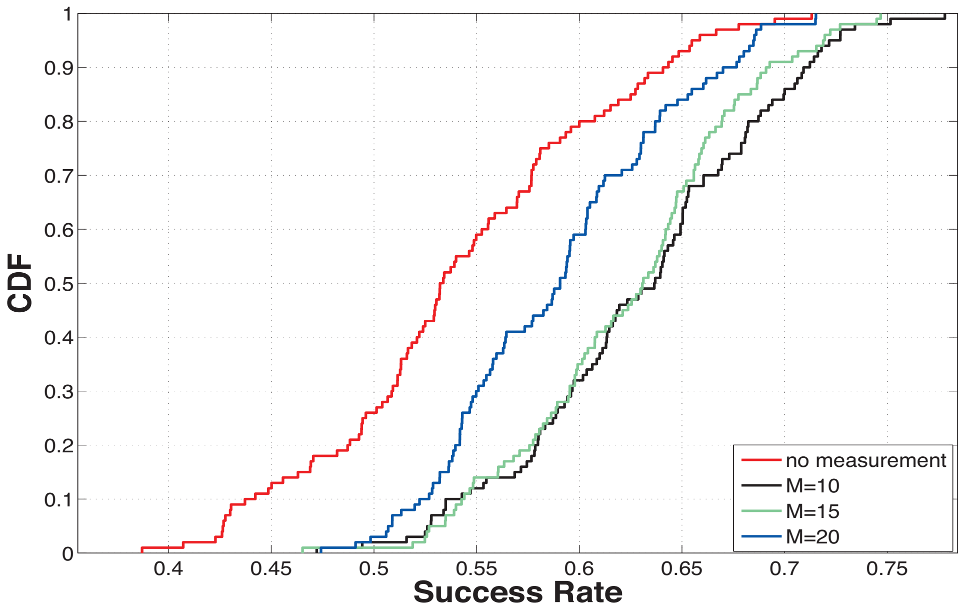


Figure 4.9: The CDF of Success Rate for Different Distances Between Measured Slots.

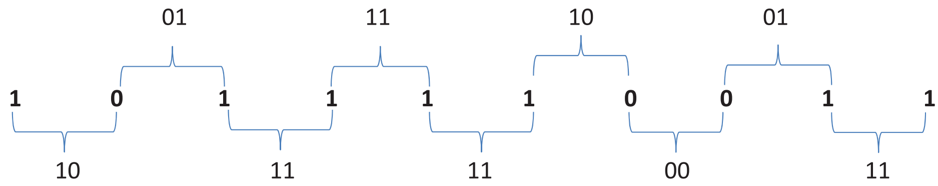


Figure 4.10: Sequence of Acknowledgement Packets Signifying either Successful or Failed Packet Transmissions and the Determination of State Transition Probabilities.

bilities. Consider figure 4.10 in which after 10 packets are transmitted in burst, the sequence of acknowledgement packets is given. The state transition is displayed in figure 4.11. From the sequence of acknowledgement packets, it can be seen that altogether there are 9 transitions: once from 0 to 0, twice from 0 to 1, twice from 1 to 0 and four times from 1 to 1. Hence the state transitions probabilities, in respective order, are: $\frac{1}{9}, \frac{2}{9}, \frac{2}{9}, \frac{4}{9}$. Once the state transition probabilities are determined, the expected burst size can be calculated once again by applying equation 4.15. It must be noted that the sequence obtained in figure 4.10 is not sufficient to produce reliable statistics. In reality, repeated experiments are conducted to obtain the state transition probabilities.

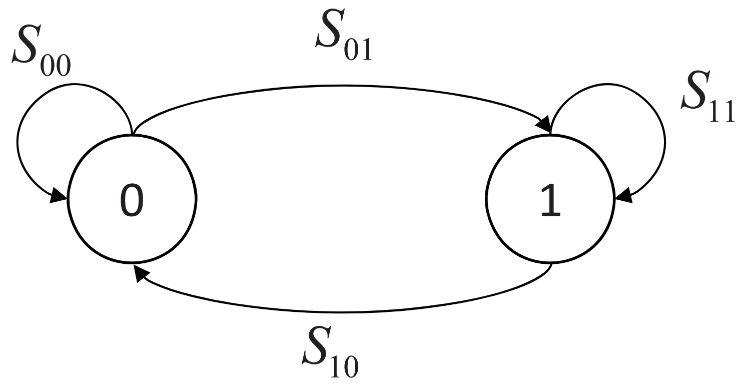


Figure 4.11: A Two-State Markov Process Modelling Burst Transmission within a Link Quality State.

4.5 Evaluation

To evaluate the efficiency of the propose scheme in this chapter, Mobilab is deployed for indoor and outdoor environments. The distance and transmission power between the nodes is arbitrarily varied from 10 to 45 m and from -3 dBm to -15 dBm, respectively, to obtain different link qualities. Two indoor and three outdoor links are selected. I transmit more than 300,000 packets both to obtain statistics pertaining to link quality fluctuations and to test the propose approaches. During a continuous transmission of packets, the inter packet interval (IPI) is set to 20 ms as described in table 4.1, so that each node has sufficient time to receive packets and to locally store link quality metrics.

The performance of the proposed models, the Conditional Probability Bases (CPB) and Double Markov Based (DMB), are compared with the ‘Baseline’ approach in which packets are transmitted in burst without taking knowledge of link quality fluctuation into account. The reason to compare these with the ‘Baseline’ approach is to show the gain in the performance of the burst transmission scheme when the underlying link quality fluctuation is taken into account. Since most of the burst transmission protocols did not take link quality fluctuations into account.

4.5.1 Optimal Cluster Size for the DMB Model

Previous studies suggest that link quality can be categorised into three states, namely, good (perfect), intermediate (bursty), and bad. Since this is a plausible classification, it is possible that it does not apply to all kind of links. In our investigation to find the optimal size of k, different values of k are considered and the packet success rate of different links is measured.

The Packet Success Rate (PSR) is a metric used to measure the performance of transmission protocols. The packet success rate for transmitter 't' is define as the ratio of the number of packets successfully acknowledged given a total number of transmitted packets. It can be described as follows:

$$PSR_t = \frac{ACK_t}{PKT_t} \tag{4.16}$$

Where, ACK_t is the number of ACK packets received by the transmitter t in 'T' seconds and PKT_t is the total number of packets transmitted by transmitter t in 'T' seconds. Figure 4.12 compares the packet success rate for different values of k and compares the performance with the Baseline scheme. This measurement was obtained by transmitting 1000 packets for each test case and for each of the 5 selected links. Cluster sizes of 2, 3, and 4 are considered. As can be seen from figure 4.12, the DMB model improves packet delivery, regardless of the value of k. Nevertheless, for links 1, 3, and 5, the value of k that resulted in the highest packet delivery was 4, whereas for link 2, it was 2, and for link 4 it was 3. The reason for this is the size of the transitional region. If the size of the transitional region is small meaning close to zero, then the link can be described perfectly with only two states because it is either good or bad. As the size of the transitional region increases, it is not possible to define the link perfectly by the two states of bad and good. Therefore, the third and fourth state is required to describe the transitional region completely. This explains why the cluster size depends upon the specific nature of a link.

4.5.2 Packet Success Rate

The packet success rate is one of the important performance measurement which affects the performance of wireless sensor networks. First, the packet success rate for the DMB model

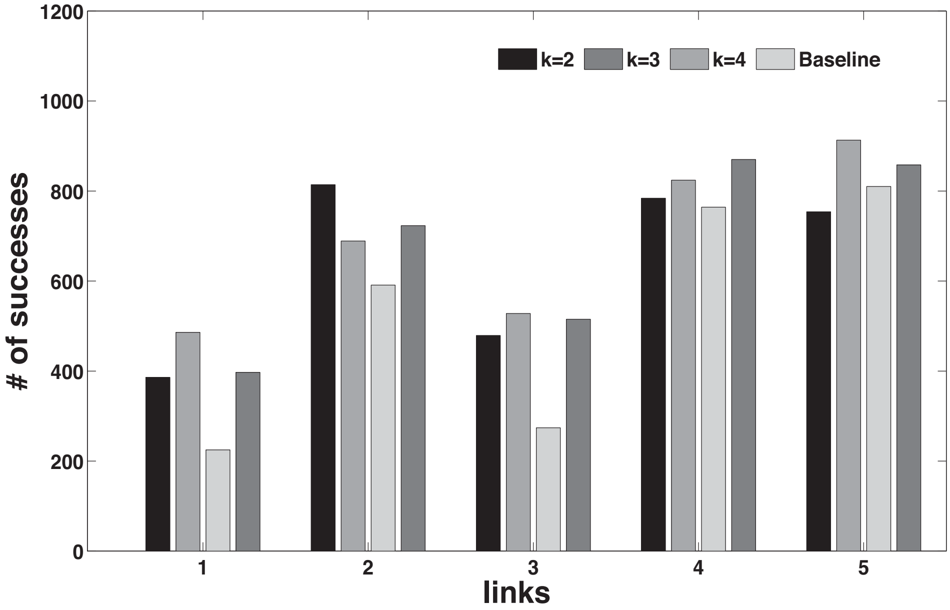
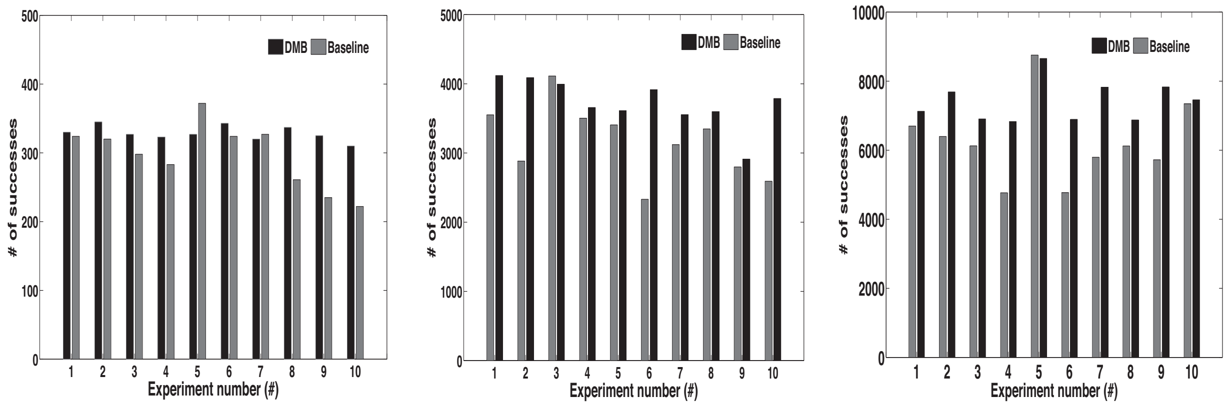


Figure 4.12: A Comparison of the Packet Success Rate of Different Links using Different values of k.

is compared with the Baseline model. To test the reproducibility of both schemes, the total number of packets transmitted are varied as follows: 500, 5000 and 10,000. Figure 4.13 shows the number of successfully transmitted packets by the DMB and Baseline approaches. For each test case the experiment is repeated 10 times and lost packets are not retransmitted. The DMB scheme has a higher number of packet successes as it is able to estimate the period of bad duration effectively and refrain from transmitting packets during that period.



(a) 500 packets (b) 5000 packets (c) 10000 packets

Figure 4.13: A Comparison of the Packet Successes of DMB Transmission Scheme with the Baseline.

Figure 4.14 compares the performance of DMB, CPB, and Baseline for 5 different links. 10,000 packets are transmitted on each link for each transmission scheme. Both schemes, DMB and

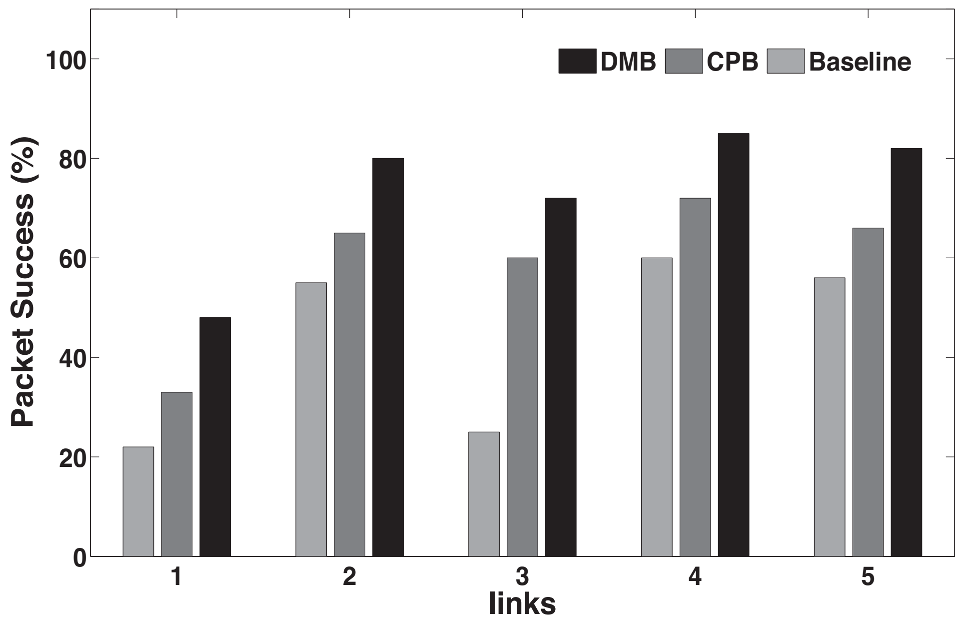


Figure 4.14: A Comparison of the Packet Successes of DMB, CPB and Baseline Schemes.

CPB, produced appreciable gain compared to the Baseline scheme (confirming the importance of an efficient transmission scheme at the MAC layer). The DMB scheme outperforms the CPB scheme on all the links because it efficiently models link fluctuation into different states. In the DMB model, burst transmission takes place within a single state followed by a pause before a state transition takes place, which means, the maximum burst size within a state is bound by the duration of the time slot. In contrast, using the CPB model yields no notion of state. A burst can have any size. Each bar graph represents the average outcome of 10 repeated experiments.

4.5.3 Transmission Time

Transmission time is defined as "the amount of time required to transmit a single packet from source to destination". This is similar to throughput. Figure 4.15 shows the time required to transmit 1000 packets successfully from the source to the destination by each scheme. Lost packets are retransmitted in this experiment by all transmission schemes. Each transmission scheme transmits packets until all the transmitted packets are successfully acknowledged. The Baseline model has the lowest transmission time compared with the CPB and DMB models because of the fact that it transmits packets continuously with out any interruption. The CPB scheme has the highest transmission time due to its inherent feature (use fix threshold) which

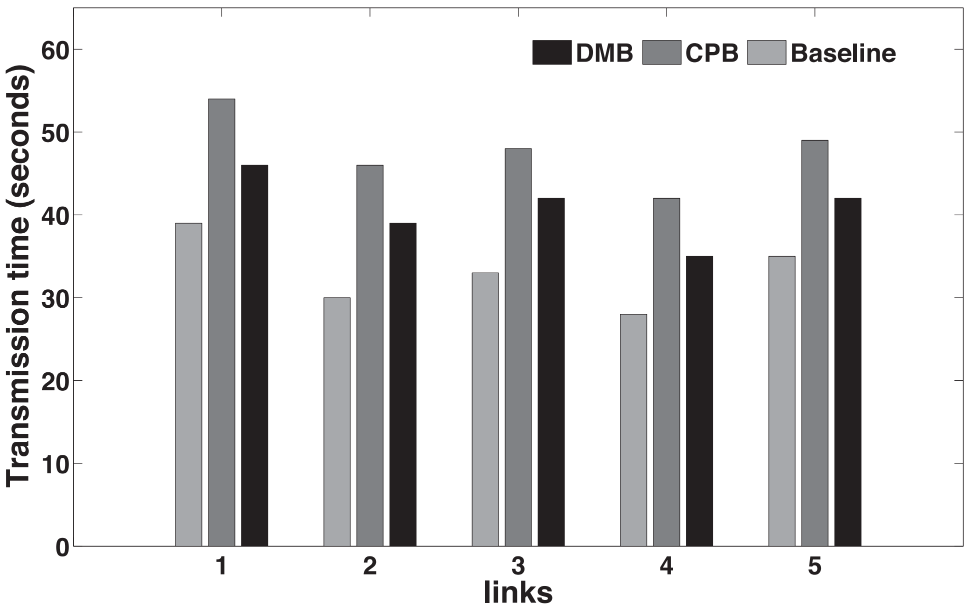


Figure 4.15: A Comparison of the Transmission Durations of the DMB, CPB and Baseline Schemes

under-estimates the quality of the link. However, the transmission time comes at the cost of higher packet loss and number of retransmission attempts. The gain of transmission time for Baseline is comparable to other techniques due to efficient modeling of link quality fluctuation by CPB and DMB methods.

4.5.4 Energy Consumption

Energy consumption is an important metric especially for low-power wireless sensor network which operates on battery power. To measure the energy consumption of the transmitting nodes, the wireless sensor network was moved to lab setting and Yokogawa digital power analysers (WT210) were attached to the transmitting node in order to measure the power. All the transmission schemes use the same configuration and should transmit 5000 packets successfully to the destination node (i.e., lost packets were retransmitted). Figure 4.16 compares the energy consumption of DMB, CPB, and Baseline. The DMB models has the lowest energy consumption due to two reasons. On one hand, it efficiently uses the good quality link period to transmit packets and on other, the DMB models refrains from transmitting packets during a bad duration. The CPB also has a noticeable gain in power consumption as compared to the Baseline approach, which highlights the importance of having link quality estimation model for burst transmission schemes.

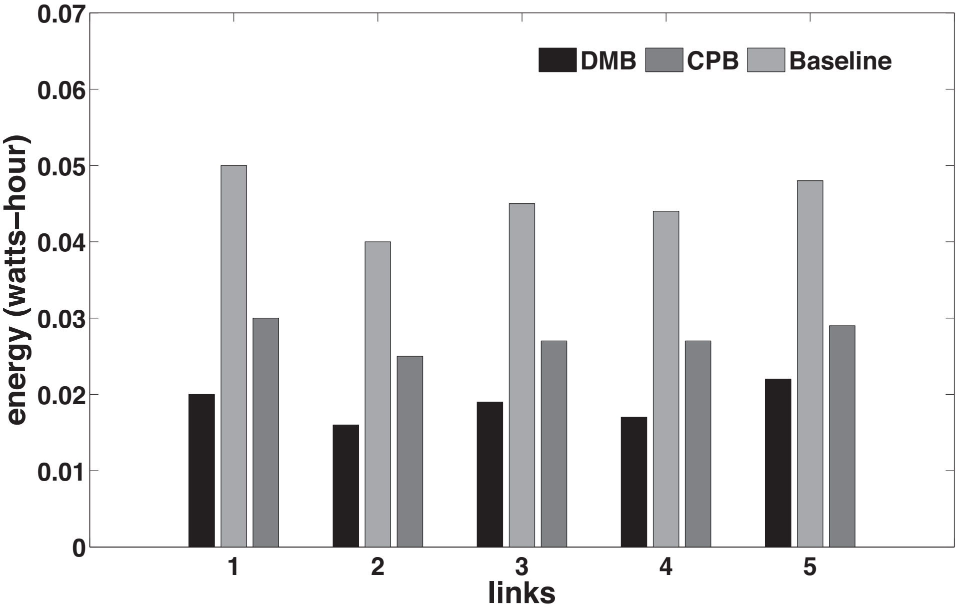


Figure 4.16: A Comparison of the Energy Consumption Levels of DMB, CPB, and Baseline Schemes

4.6 Summary

This chapter investigates long-term fluctuations of link quality in wireless sensor networks and proposes two offline schemes to estimate the expected duration of stable transmission periods. The first model, CPB, is based on conditional probability and employs conditional distribution functions where the link quality duration was conditioned by the signal-to-noise ratio thresholds of the packets that were acknowledged. The model determined the number of packets that could be successfully transmitted in burst by determining the expected value of the distribution function. In other words, nodes transmit packets in burst when the link quality is good but they refrain from transmitting packets when it is bad. The problem with the proposed model is choosing the value of the SNR threshold. There is no possible way to define a single value for all types of links. The empirical study reveals that the size of the transitional region varies for different link quality. Hence, the CPB approach is unable to model the transition region due to its very construction.

The problem of the CBP approach is addressed by modelling the link quality fluctuation using a two-stage Markov model called the DMB. The DMB approach can be realised in three steps: first the link quality fluctuation is divided into countable regions using a k-mean clustering algorithm. Due to different sizes of the transitional regions, the DMB scheme applies the *silhouette method* to identify the optimal number of regions to sufficiently characterise link quality fluctuation. These regions as states model link quality fluctuation in a discrete Markov process. Second, the statistics from the ARR vs. the SNR relationship are used to determine state transition probabilities. Using state transition probabilities, the expected duration a link stays in a given state is computed. Third, for each state, the DMB scheme estimates the number of packets that can be transmitted in burst by applying a discrete Markov process on the binary sequence constructed from received acknowledgement packets.

To test the plausibility of both DMB and CPB approaches, an extensive experiment is performed in different environments. The proposed schemes are compared with the Baseline approach in which no link quality estimation model is employed. The CPB and DMB models are evaluated on five different indoor and outdoor links which have been set up with different physical layer parameters. The TelosB and Imote2 nodes are use to set up the wireless sensor networks. To model CPB and DMB, 150,000 packets are transmitted on five different links with a number of different configurations as shown in table 4.1. Then to evaluate the performance of DMB,CPB and Baseline models, additional 150,000 packets were transmitted. The result of these experiments confirm that both CPB and DMB approaches improves the packet success up to 40% on different wireless links as compared with the Baseline approach. The DMB scheme outperforms the CPB schemes and improves the packet success rate up to 25%. The packet success rate is improved due to the efficient burst size calculation. The gain in packet success and failure reduces the number of re-transmitted packets which eventually results in reducing the energy consumption.

Our approaches DMB, and CPB, assume that if the link quality fluctuation is observed for a sufficiently long time, then its statistics can be considered stationary in a wide sense. As a result, all the parameters that make up our model are static. This, however, may not always hold true and the parameters should be adjusted when the nature of link quality fluctuation changes. Our future goal is to address this issue.

Chapter 5

An Online Link Quality Estimation Model for WSNs

The primary shortcoming of an offline approach is its inability to deal with short-term link quality fluctuations. In order to exploit intermediate bursty links, the transmission scheme needs to handle both long-and short-term link quality fluctuations. Sufficient statistics can be collected to estimate long-term link quality, hence helping predict the fate of future transmitted packets over a long period of time. On the other hand, the transmission scheme must learn the current state of the channel in order to deal with short-term link fluctuation.

In this chapter, a hybrid burst transmission scheme, namely ”H-DMB”, [AWD16] is proposed. It deals with both long-and short-term link quality fluctuation. The ‘H-DMB’ scheme has two phases: offline and online. In the offline phase, the H-DMB scheme models the link quality fluctuation using a two-stage Markov model. The model (a) classifies the link quality into different states and determines the transition probabilities between the states; (b) estimates the average number of packets that can be transmitted in each state and (c) estimates the expected duration of a link staying in a particular state. During the online phase, the “H-DMB” uses the short-term data of the received acknowledgement packets to predict the most probable future state and the associated burst size.

5.1 Offline Phase

To model link quality fluctuation in offline phase, the "H-DMB" scheme uses machine learning techniques. This hybrid scheme first classifies link quality into different clusters (or states). It then determine the transition probability between the states. It also estimates the average duration of a state and the optimal number of packets that can be transmitted in this state. The mechanics of an offline phase are briefly described below (for details please refer to chapter 4):

1. Using data collected from our sensor network, a relationship between the SNR and the ARR is established. On the basis of the established relationship, k-mean clustering is employed to model link quality fluctuation into different states.

2. State transition probabilities are calculated to establish a relationship between the states. Expected state duration (ESD) can also be known by using the probability density function of the states.

3. The last step of the offline phase is to determine the total number of packets to be transmitted in each state which is found by employing the first order Markov chain with two states.

The idea of using k-mean clustering and the Markov model can be straightforward, but it is computationally expensive and therefore cannot be computed in real time. Therefore, the H-DMB model employs the look-up table to save the information calculated offline. It contains the number of states, the duration of each state and the burst size of each state. The look-up table will not change during the operation of the node so it can be computed offline and embedded into the node. The advantage of the offline model is the availability of large channel statistics and the ability to employ complex algorithms such as k-Mean clustering and the Markov model to model long term characteristics of the channel. However, the disadvantage is that it reacts poorly to short-term link quality fluctuation, as the proposed scheme is optimised for long term link quality fluctuation. Moreover, there is no real-time feedback mechanism to correct wrong state transitions.

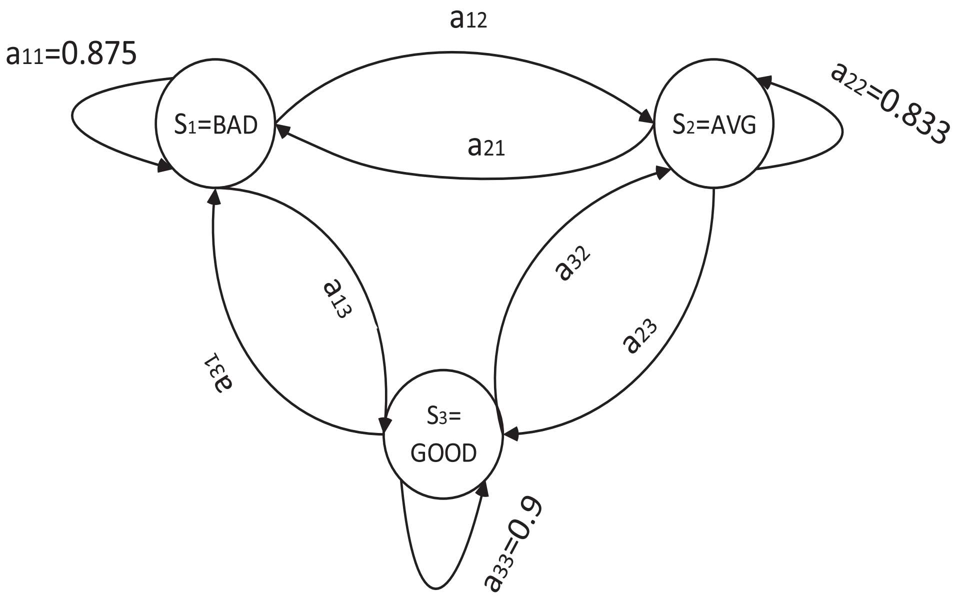


Figure 5.1: An Example of 3 State Markov Chain.

5.2 Online Link Fluctuation Model

Although the offline model reflects the long term characteristic of a link, it fails to deal with short-term link fluctuations. Since the state transition is a probabilistic phenomenon, the model may generate erroneous transitions, or it may fail to “perceive” short-term proper transitions. The cumulative effect of both cases may lead to a link fluctuation perceived by the model which does not occur in reality. This point is highlighted by an example in which a given link under observation is modelled by a three-state Markov chain with transition probabilities. This is shown in figure 5.1. The ESD and the burst size are calculated by applying equation 4.15 and the results are stored in table 5.1. A detailed pictorial overview is depicted in figure 5.2, where, at time T, the offline model accurately estimates the channel to be in the state 1 (S_1=Bad). According to table 5.1, the link quality should remain in the same state for next 8 time slots. However the state duration differs with the expected state duration estimated by equation 4.15. It is also evident from the same figure that the link quality changes to state 2 (S_2=Intermediate) at time $T+2$ and to state 3 (S_3=Good) at $T+5$, which cannot be detected with out the knowledge of the real-time channel feedback. In order to assess the problem of short term transitions, an online model is required. The main purpose of this model should be to fine-tune or calibrate the off-line model.

Figure 5.3 shows the components of the online model, which, are depicted as a look-up table

Link State	Burst Size	ESD
Good (S_3)	10	6
Intermediate (S_2)	6	4
Bad (S_1)	2	8

Table 5.1: Expected State Duration and Burst Size of Different States.

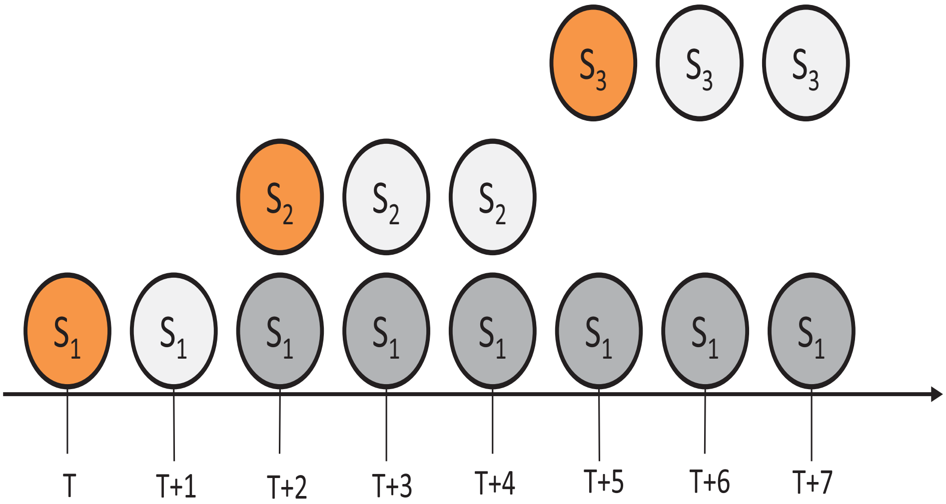


Figure 5.2: A short term state transition that may not be "perceived" by the offline model. The orange states indicate proper transitions, the light-grey states indicates actual link quality states, and the dark-grey states indicate the estimated link quality state by the off-line model.

containing the state transition matrix generated by the offline model, a channel state estimator evaluating the link quality metric of the incoming acknowledgement packets and determining to which state the current link quality belongs, and this metric serves as a predictor estimating the next state of a link and the number of packets that should be transmitted in burst.

One of the challenges of relying on an online link quality estimation mechanism is the difficulty of gathering sufficient statistics. This is the case especially for bad and intermediate states, where the number of successfully delivered packets is scant. Thus to simplify my online estimation, a metric called *conditional probability of expected state duration* (CPESD)[1] is defined. The idea is as follows: suppose the expected state duration for a bad state is 8. In other words, once the link quality transits to a bad state, it stays there for the next 8 state durations (recall that a single state duration equals the time required to transmit 10 packets). The CPESD expresses the probability that the link quality stays as predicted by the model, assuming that the past n states were as estimated by the model. Figure 5.4 displays the CPESD of a bad state for different links established outdoors. If the link stays in the same state for at least

[1]The essential notion is first proposed in [LCL07] and adopted in [SAAP08] and [AWK+11].

three consecutive state durations, the link will stay as predicted by the offline model for – 70% of the time [AWD16].

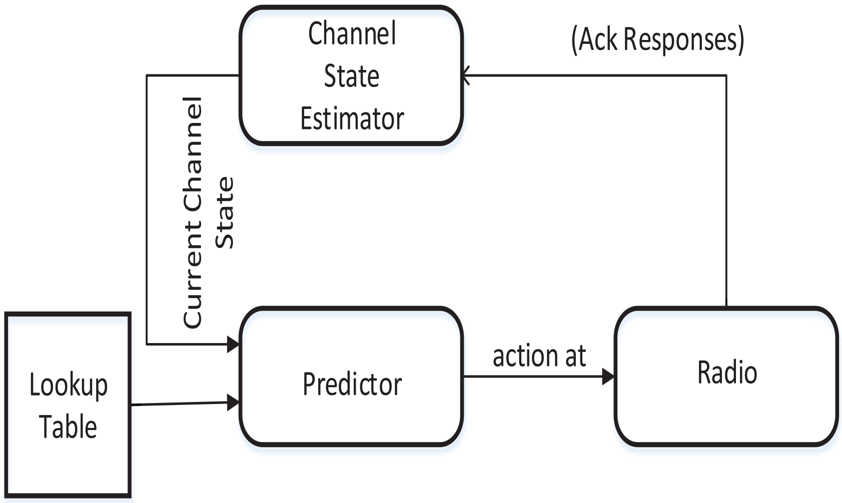


Figure 5.3: The System Architecture of the Online Link Quality Estimator.

5.3 Algorithm

In order to illustrate the functionality of the online transmission scheme, a look-up table (table 5.1) is filled with data obtained from the offline model for one of our links. Initially (in the time slot T), the burst transmission strategy transmits 10 packets in succession (the maximum number of packets that can be transmitted in a single state). Based on the number of packets successfully received along with the average SNR of the received acknowledgement packets, the channel state estimator determines the current link quality state. If the outcome of current link quality state is *good*, the link quality remains in the same state for the next 6 consecutive time slots and the online transmission scheme continues to transmits 10 packets in burst in each subsequent time slot.

Contrary to the above scenario, if after the initial burst transmission only 2 packets are successfully delivered, then the link quality is in the *bad* state. The offline strategy would have only transmitted 2 packets per state duration for the next 8 state durations (as shown in table 5.1). However, this would not create sufficient statistics to determine the short-term link quality fluctuation during this time. Therefore, the online transmission scheme considers the

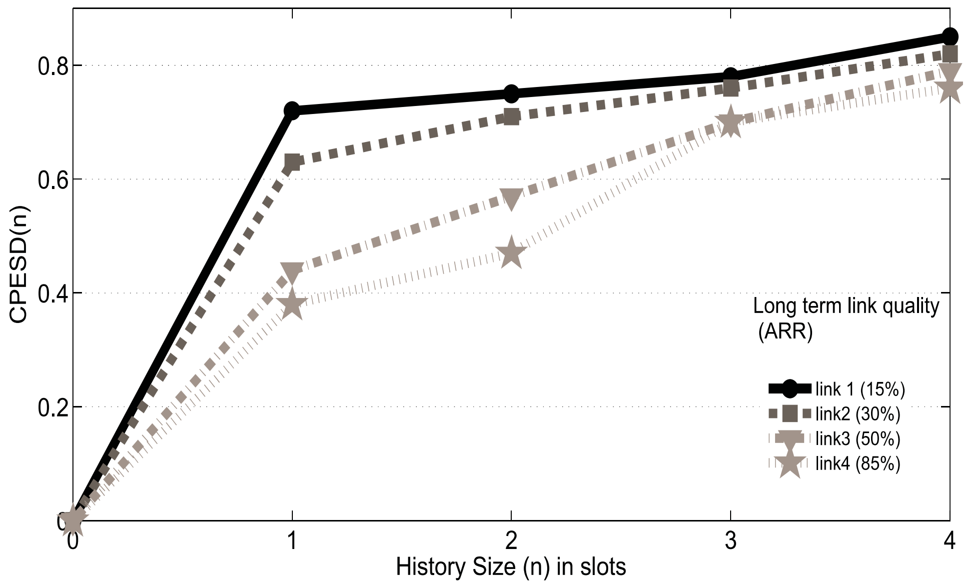


Figure 5.4: Measuring the Prediction Accuracy of a Bad State from a Short History.

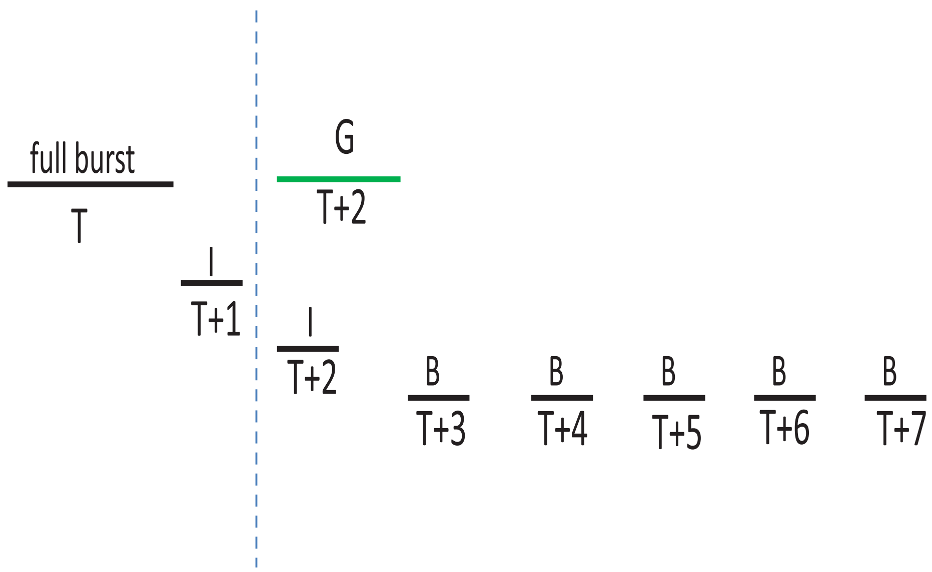


Figure 5.5: An Online Burst Transmission Strategy. G: Good State, I: Intermediate State, B: Bad State.

link quality of slot $T+1$ as an intermediate state and sends 6 packets in burst (this is indicated in Fig. 5.5). At this stage if all the 6 packets are delivered successfully, the transmission scheme considers the link quality as *good*. It increases the number of packets (10 packets) to be sent in burst in the next time slot ($T+2$) (indicated by the green line in Fig. 5.5). On the contrary, if 2 or less packets are successfully delivered similar to slot $T+1$, the link quality is still in a *bad* state. However, the transmission scheme continues to transmit 6 packets in burst to gather enough statistics. If the SNR of the received acknowledgement packets still indicates a *bad* state link in the time slot $T+2$, then according to CPESD, the link has been in the *bad* state for the past 3 state durations. It will remain in the same state for the average duration determined by the offline model (the next 5 states for our example). Hence, it transmits only 2 successive packets in the next 5 time slots. After $T+7$, the online scheme determines the next state based on the acknowledged packets for state $T+7$ and repeats the same procedure.

Algorithm 1 summarises this online transmission scheme where O_T refers to the link quality state for the time slot T; $CPESD_{th}$ refers to the minimum number of state durations which results in $CPESD \geq 0.7$ (for our case, $CPESD_{th} = 3$); P_{T+1} is the predicted state for the time slot $T+1$, and S_i is the link quality state, defined as *good*, *intermediate*, and *bad* [AWD16].

Algorithm 1 Transmission Technique

```
Input:O_T, CPESD_th
Output:P_{T+1}
initialisation:S_3 = Good, S_2 = Average, S_1 = Bad
if O_T ≠ S_3 then
    if O_T == S_i  where,  i≠3 then
        if O_T == O_{T−1} then
            Count++
        else
            Count=0
        end
        if Count < CPESD_th then
            P_{T+1} ← S_{i−1}
        else
            Stay for the duration of (ESD − CPESD_th) in state S_i
        end
    end
else
    P_{T+1} ← O_T
end
```

5.4 Implementation and Evaluation

To evaluate the performance of the proposed burst transmission scheme (H-DMB), it will be experimentally compared with two state-of-the-art schemes. One of them is the β-factor (or simply β), developed at Stanford University by Srinivasan et al. [SAAP08]. The other is the Bursty Link Estimator (MAC_3), developed at RWTH Aachen University by Alizai et al. [AWK+11]. For experiment purposes, all transmission schemes are implemented and integrated into the TinyOS environment and the TelosB platform, followed by deploying Mobilab testbed consisting of 14 nodes in an outdoor environment. These 14 nodes are placed randomly keeping a minimum and a maximum distance of 10 m and 45 m, respectively, between the nodes. The wireless channel used for communication is channel 26 with different RF transmission power levels ranging from the minimum to the maximum (i.e., levels 1 to 31) establishing five different links for communication[AWD16].

For the H-DMB model (to establish the offline statistics), 2,000 packets are transmitted in each link with an Inter Packet Interval (IPI) of 20 ms and gathered from the received acknowledgement packets RSSI, LQI, background noise, and timestamps. I determined (1) the number of distinct link quality states for each link using a k-means clustering algorithm; (2) the link quality state transition probabilities, (3) the expected stable duration for each state and (4) the expected number of packets that can be transmitted in burst for each state. These link quality metrics are then entered into a look-up table and flashed to the nodes to be referred to during online adaptation.

In contrast, the β factor divides time into 500 ms slots and transmits packets in burst within these slots. The number of packets that can be transmitted in a single slot depends on the IPI. So when the IPI = 20, 25, 50, and 100 (ms), a maximum number of 50, 40, 20, and 10 packets can be transmitted in burst within each slot, in respective order. When packet transmission fails (no acknowledgement packets are received), β halts transmission for the remaining period of slot and resumes with the burst transmission from beginning of the next slot.

The other compared scheme, MAC_3, first transmits 100 packets in burst and uses the history of the acknowledgement packets to determine the size of the next burst transmission. After each transmission period, a new acknowledgement sequence is added to the link history.

The performance of all the three transmission schemes is compared for a single hop link using

Table 5.2: A Summary of Physical Parameters used to Establish the Links.

	Link1	Link2	Link3	Link4	Link5
d (m)	35	15	15	10	22
P (dBm)	0	-10	0	-10	-3
Location	outdoor	outdoor	indoor	indoor	outdoor
IPI (ms)	25	100	20	25	50

the following metrics: (1) **throughput:** the number of packets successfully acknowledged per second, (2) **transmission time:** the time required to successfully transmit 'n' packets, (3) **packet loss**: the number of lost packets after transmitting 'n' number of packets, and (4) **energy consumption:** the energy consumed by transmitting nodes to deliver 'n' packets successfully. Table 5.2 summarises the transmission parameters of each link.

5.4.1 Throughput

Throughput is an important evaluation metric in wireless sensor networks, particularly for aggregating nodes which are closer to a base station. It refers to the speed with which a node successfully delivers packets to its neighbour. In other words, throughput refers to the number of successfully acknowledged packets per unit time. Figure 5.6 compares the throughput of our scheme with the two online transmission schemes where 20,000 packets are transmitted over each link by considering different IPIs, as described in table 5.2. Each bar graph represents the average throughput of 10 repeated experiments. In all cases, the H-DMB model has the highest throughput. The reason is that the H-DMB model deals with short-term link quality fluctuations by reducing the burst size when the link quality deteriorates and resuming transmission with the maximum burst size as soon as the quality of the links improves. However, β differs transmission for fixed values as soon as it encounters a single packet failure but regards all failures as similar even though the underlying conditions are different. The MAC_3 has the longest reactive time for short-term fluctuations since its history size is fixed. Moreover, even for a longer observation period, the expected burst size for the MAC_3 is comparatively small (between 6 to 10 packets per burst). Due to this small burst size the history array holds outdated history and, as a result, the future burst size is often wrongly calculated. The throughput of the H-DMB model is twice as high as β and three times higher than the MAC_3 on average.

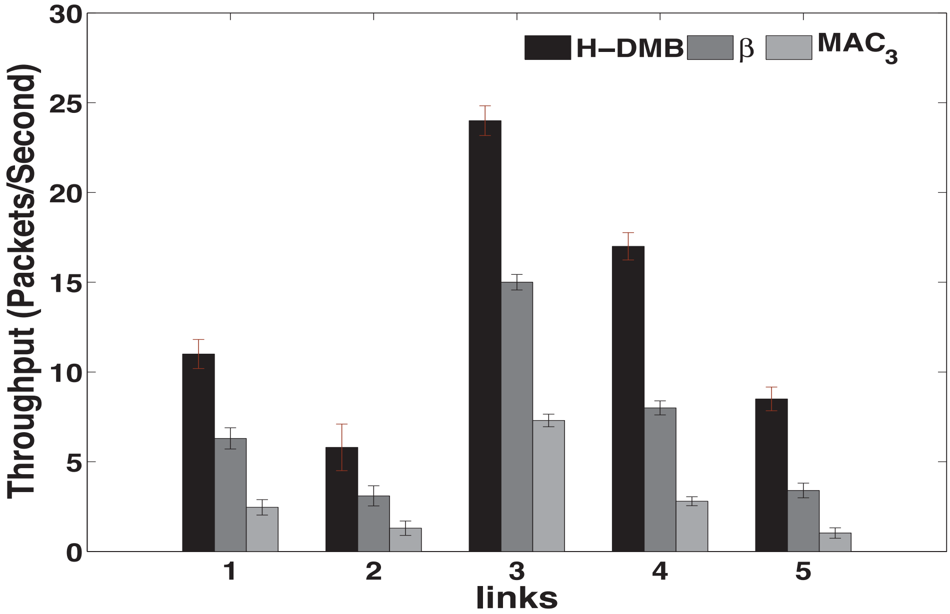


Figure 5.6: A Comparison of the Throughput of the Three Burst Transmission Schemes for Different Wireless Links.

5.4.2 Transmission Time

Transmission time (or delay) is another way of looking at throughput. It refers to the time required to successfully transmit a fixed number of packets. The term "successfully" indicates retransmission of lost packets. Figure 5.7 displays the time required to transmit 5000 packets successfully in different links. In accordance with the results we observed for the throughput, the H-DMB model performs better than the others in all the links. The transmission time of the H-DMB model is reduced on average by half and three times in comparison to the transmission time of β and MAC_3, respectively. The advantage of the H-DMB over β and the MAC_3 is its ability to deal with both isolated losses and losses in burst. β cannot differentiate between isolated and correlated losses and behaves in a similar manner with regard to all types of losses. This reduces the packet loss rate over the expense of higher transmission delay as evident from the figure 5.7. In comparison, when transitioning from bad to good link quality, the MAC_3 has the highest transmission delay due to its slow response time.

5.4.3 Packet Losses

Packet loss rate is another important metric to compare the performance of communication protocols. The packet loss rate is directly related to the retransmission cost as the number of

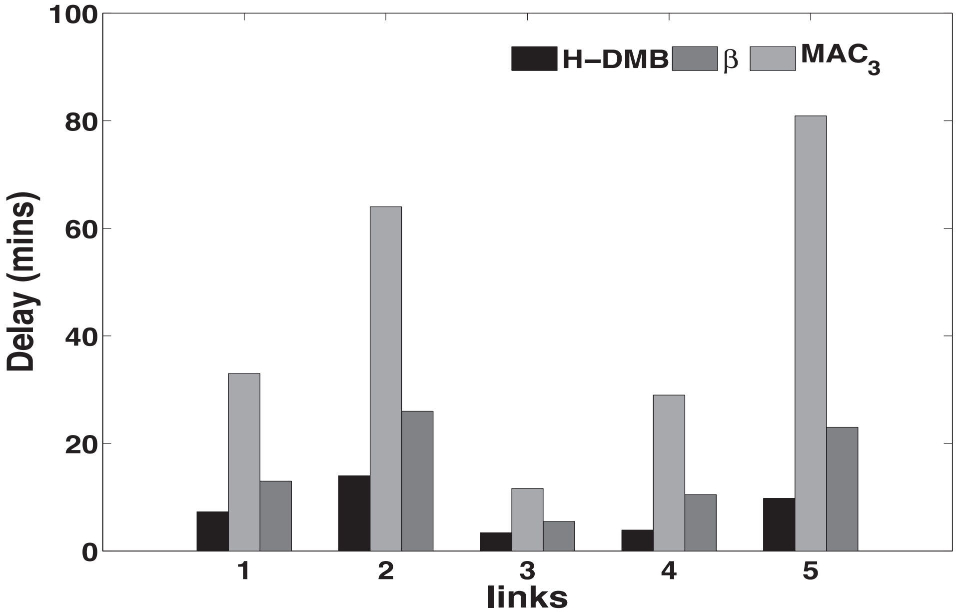


Figure 5.7: A Comparison of the Time Required to Transmit 5000 Packets Successfully. Lost Packets were Retransmitted until all the 5000 Packets were Successfully Transmitted.

packet loss increases the re-transmission cost simultaneously. Figure 5.8 compares the percentage of packets lost during the transmission of 5000 packets over different links. As can be seen, the MAC_3 has the highest percentage of packet losses due to its slow reaction to link quality fluctuations apparently as a result of facing difficulty in determining the suitable burst size. β has the lowest packet losses in comparison to other schemes because of its aggressive nature in dealing with link losses by halting packet transmission upon single packet failure. The H-DMB model exhibits a 4 to 10 percent higher packet loss in comparison to β, as it does not halt packet transmission on a single failure, which results in separating the isolated packet loss from the burst losses. When the quality of the link deteriorates, first the H-DMB model does not halt the packet transmission immediately instead, the model considers it as a short-term link fluctuation and second, reduces the burst size for the period of the CPESD threshold value. If the link quality does not return back to a good state during this period, then packet transmission is halted. This strategy increases throughput and transmission delay as evident from the evaluation results. It also increases the packet loss rate.

5.4.4 Energy Consumption

In order to measure the amount of energy consumed by the transmitting nodes, the wireless sensor network is deployed in a lab environment and the Yokogawa digital power analyser

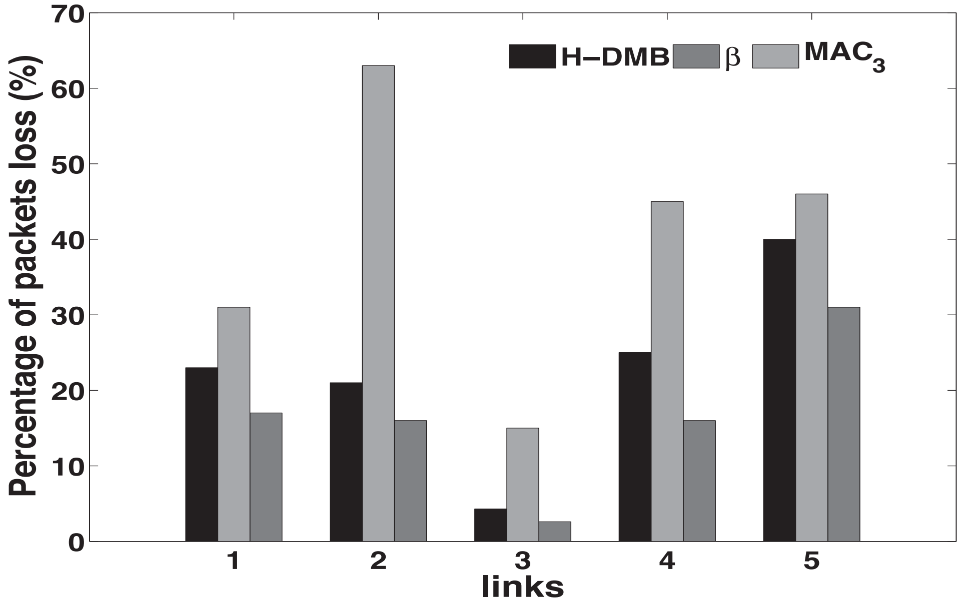


Figure 5.8: A Comparison of the Percentage of Packets Lost During the Transmission of 5000 Packets with the Three Burst Transmission Schemes.

(WT210) is used. All transmission schemes use the same configuration and should deliver 2000 packets successfully (i.e., lost packets are retransmitted). The power analyser can support the maximum sampling rate of 10 samples per second, i.e., a minimum of 100 ms interval between each sample. Therefore, in order to match the power sampling frequency with the power consumption of the transmitting nodes, the inter-packet-interval is set to 100 ms. Figure 5.9 shows the actual energy consumption in watts-hour. The TelosB nodes consume 0.055 watts of energy to transmit a single packet. The transmission scheme with the highest consumption of energy was the MAC_3 because of the fact that it had the highest number of packets retransmitted resulting in a prolonged transmission time. The next scheme which consumes high power is β, because it has a longer transmission delay in comparison to the H-DMB model. This eventually keep the radio active for a longer duration of time. The H-DMB model consumed the least amount of energy in all the links due to the fact that it had the highest throughput and lowest transmission delay.

5.5 Summary

This chapter proposes a hybrid burst transmission scheme H-DMB for the IEEE 802.15.4 wireless link to enable a relatively higher throughput. In order to deal with link quality fluctuations

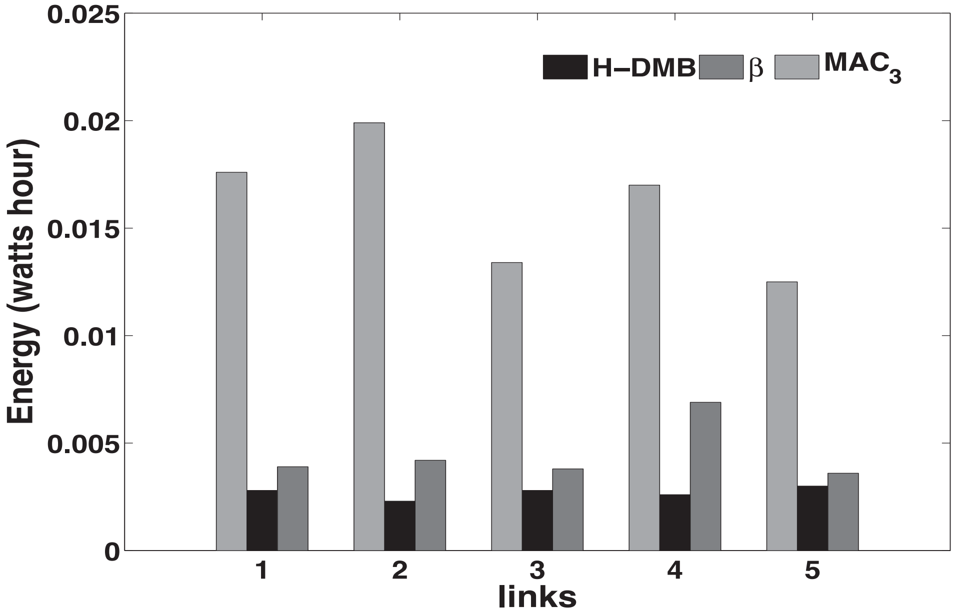


Figure 5.9: A Comparison of the Energy Consumption of the Three Transmission Schemes when Successfully Delivering 2000 Packets in an Indoor Environment (Lab Setting).

and reduce packet losses, the H-DMB approach combines offline and online models. The offline model is a two-stage Markov model which classifies link quality fluctuations into different link states and associates transition probabilities to these states. Furthermore, using these transition probabilities it estimates the expected duration of each link state and the expected number of packets to be transmitted in burst in each state. This offline model is optimal in characterising long-term link quality fluctuations. It is however unable to deal with short-term link fluctuations. The online model, on the other hand, "perceives" short-term link quality fluctuations and attempts to make appropriate transitions. Consequently, the integration of both models into a unified transmission scheme enables it to deal with both short- and long-term link quality fluctuations.

The H-DMB approach and two additional state-of-the-art burst transmission schemes (β and MAC_3) are implemented and integrated into the TinyOS environment for the TelosB platform. We deployed a wireless sensor network consisting of 14 TelosB nodes in indoor and outdoor environments and experimentally compared the performance of the three transmission schemes in terms of throughput, bulk transmission delay, packet loss, and energy consumption. The H-DMB approach resulted in having the highest throughput, the shortest transmission delay, and the least amount of energy consumption, but β proved to have the least packet loss while the performance of MAC_3 was the worst in terms of all the metrics defined in this thesis. The MAC_3 had a slow reaction time and difficulty in obtaining the optimal burst size suitable for the current link quality hence affecting its performance immensely. However, the performance of the MAC_3 can be improved by using an adaptive history size over a fixed history size and by defining a new metric to calculate the packet halt duration. Similarly, the performance of the β scheme can also be improved by finding an optimal number of packets required to be re-transmitted before halting a packet transmission. Furthermore, defining β requires a large data set making this metric unsuitable for online approaches, given that in real-time sensor nodes have limited available memory. Lastly, the performance of the H-DMB model can also be improved by updating the look-up table in real-time. Currently, the H-DMB characterises channel in a pre-deployment phase and stores the result in a look-up table which has no update mechanism. Therefore, as the deployment environment changes the values in the look-up table becomes obsolete.

All the transmission schemes proposed until now namely CPB, DMB, and H-DMB are designed and developed for static wireless sensor networks and does not take into account the mobility of wireless nodes. Mobility plays a key role in many applications. In healthcare, where biomedical sensors are attached to the human body to monitor vital parameters; in animal monitoring sensor nodes being attached to animals to monitor their movement patterns and production; in smart cars they are embedded in cars for vehicle-to-vehicle communication. The next chapter discusses the link quality fluctuation introduced by mobile nodes and proposes a design of an efficient transmission scheme by modelling the underlying link quality fluctuations.

Chapter 6

A Link Quality Estimation Model to Support Mobile Nodes in WSNs

This chapter proposes an estimation model for link quality fluctuation of mobile sensor nodes. Wireless sensor networks supporting mobile nodes and applications which require high throughput can benefit from bulk data transfer protocols. Unlike conventional medium access control protocols, which force each competing node to contend for each packet it transmits, bulk data transmission enables a node to use a channel exclusively for transfer of a large amount of data in succession. Existing or previously proposed MAC protocols that support bulk-data transmission, however, are unresponsive to link quality fluctuation. Nodes make repeated attempts to retransmit lost packets even when the statistics of the received packets suggest that the channel is still bad or that packet transmission will be deferred arbitrarily even though packet loss is an isolated and uncorrelated occurrence.

Nevertheless, bulk data transmission alone cannot be an adequate solution if the underlying link is not stable, as this will lead to wasting already scarce resources. This shortcoming was first addressed by Duquennoy et al. [4], who proposed a generic "burst forwarding" (BF) technique which (1) uses radio duty-cycling to overcome the period of bad link quality and (2) provides high throughput by using multiple channels as opposed to a single channel to avoid inter and intra path interferences. However, the proposed approach employs CSMA technique with exponential back-off to reduce the number of retransmissions of lost packets. Exponential back-off, unfortunately, is inefficient in wireless sensor networks when mobile nodes are involved and when the nodes are subject to high interference.

In mobile wireless sensor networks (MWSNs), the link quality fluctuates more rapidly in comparison to static deployment due to changing environment, path-loss, fading, the Doppler effect and shadowing. One of the formidable challenges in a mobile scenario is to deal with impulsively changing bursty links. It is evident from the empirical study (Chapter 3) that in a mobile scenario, the percentage of intermediate links is higher than the static scenario as the transmission success rate fluctuates strongly over a short period of time. Also, fluctuation of the link quality depends on the node movement, speed, and direction. This is a random process and cannot be regarded as stationary as assumed in the case of static scenario. This lead to the conclusion that an online link quality estimator which adapts to the short-term link quality fluctuations in real time is a pre-requisite in a mobile environment to achieve high throughput while maintaining low power consumption.

6.1 Approach

In order to motivate our proposal, consider figure. 6.1. Suppose the quality of a given wireless link is described as shown in the figure (top). The threshold line is drawn to suggest that packets with a link quality metric below this threshold will not be delivered successfully. If a transmitter has this information *a priori*, it will stop transmitting exactly before the link quality falls below the threshold line. It will resume transmission when it rises above the threshold line. But this information is hard to obtain *a priori*. One of the proposed approaches in the literature, the β-factor, suspends transmission upon a single packet failure (shown in the figure. 6.1(a)) for a specific amount of time, then it resumes burst transmission. If, upon resuming the trajectory, the packet is still lost, the scheme suspends transmission once again for the same duration. During suspension, the radio is turned off to save energy. The suspension period is determined empirically. The second approach, *Pushback*, also suspends packet transmission on a single failure (shown in the figure. 6.1(b)). However, unlike the β-factor it calculates the duration of the halt period online by combining real-time channel feedback with offline model by using a look-up table. The third approach, *burst forwarding*, does not suspend transmission upon a single packet failure (shown in the figure. 6.1(c)). Instead, it attempts to retransmit the lost packets, but if the attempt is not successful for the n-th time, it performs a random back-off

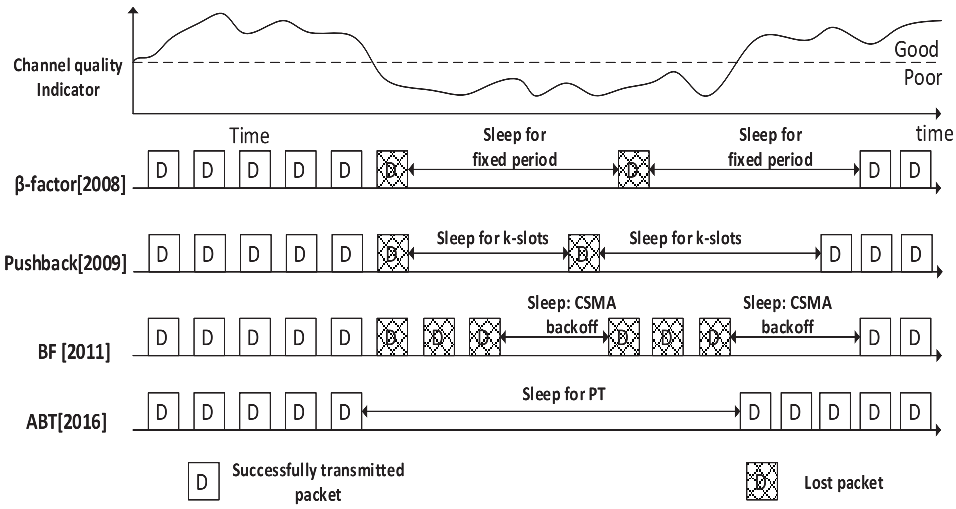


Figure 6.1: A Comparison of Different Burst Transmission Strategies (β-factor, Pushback, BF and ABT) to Deal with Frequent Link Quality Fluctuations.

before it attempts to resume transmission. If it still experiences failure, it increases the back-off window exponentially and performs a random back-off once again.

A more efficient approach would be to rely on the statistics of incoming ACK packets in order to determine the expected durations of good and bad states. In static deployment, the link quality fluctuation statistics can be regarded as stationary in a wide sense, in which case, it is sufficient to transmit a large number of packets at once, establish the statistics offline, determine the expected durations of the good and bad states, and use this knowledge to schedule packet transmission and sleep times [WAD15, ZJDW15b]. The statistics can be refreshed at runtime by evaluating the link quality metrics of received ACK packets [AWD16]. The proposed scheme in this chapter namely ABT [ZW17] (shown in the figure. 6.1(d)) estimate the duration of good and bad state by taking real-time channel feedback. It does not halt packet transmission on single or multiple packet losses.

6.2 Link Quality Metrics

When a transmitting node is mobile (assuming that the predominant traffic flow is from the mobile node to a static relay node), the link quality fluctuation cannot be regarded as stationary. Furthermore, the statistics established offline may not accurately represent the current link quality fluctuation, since it is impossible to accurately emulate or reproduce movement patterns.

Hence, the duration of good and bad states should be estimated online. Fortunately, compared to the speed of the mobile node (if the mobile node is carried by a human being), the packet transmission rate is higher. In fact, it is high enough, that it is possible to gather sufficient statistics and to predict with it the short-term link quality fluctuation. For example, with a data rate of 250 kpbs, a packet size of 28 byte, and an Inter-Packet-Interval (IPI) of 10 ms, approximately 92 packets can be transmitted in a second. If we assume that the person moves at 3 kmph and 1 m corresponds to one step, then the mobile transmitter can transmit 92 packets before the person makes a single step (or travels 0.8 m).

Suppose the mobile node transmits 100 packets in burst, some of which may fail to get delivered successfully due to a bad link. Suppose it also, collects ACK packets. From the sequence of the ACK packets, it is possible to determine the probability of successfully transmitting n number of packets in succession. Similarly, it is possible to determine the probability of losing m number of packets in succession. The expected number of packets which can be transmitted in succession successfully describes the expected duration of a good state and can be expressed as[ZW17]:

$$g = \sum_{n=1}^{100} n(p_n) \tag{6.1}$$

where p_n is the probability of successfully transmitting n number of packets in succession. Likewise, the expected number of packets which can be lost in succession describes the expected duration of a bad state and can be expressed as[ZW17]:

$$b = \sum_{m=1}^{100} m(p_m) \tag{6.2}$$

where p_m is the probability of losing m number of packets in succession. Since we have claimed that the link quality of a mobile link is not stationary, statistically speaking, the quality of the prediction we make with equations 6.1 and 6.2 depend on the history data and how well they represent the current state of the link. A fixed history size with a sliding window can be used to update link quality statistics, but this approach is inflexible. For example, suppose that after the transmission of 100 packets, we determined that $g = 10$ and $b = 6$. In other words, the mobile node transmits 10 packets in burst and sleeps for the duration it requires to transmit 6 packets. If after transmitting the 10 packets 9 of them are acknowledged, that means our prediction was accurate. ABT leaves the history size intact. If, on the other hand, the transmitter receives only 4 ACK packets instead of 10, this shows that our prediction was inaccurate. Hence, for the next prediction round, the most recent statistics are more important than the older statistics. One way to do this is by shrinking the history size and by including all the most recent statistics. Similarly, if there is consistency between the statistics of the latest data and the data residing in the history buffer, the history size can be increase gradually in order to enrich our statistics[ZW17].

6.3 Adaptive History Size

Link quality metrics (g and b) used by the ABT protocol is computed by adding new values and removing old ones from the history array at run time. Thus the history size (HS) impacts the reactivity and estimation error of the link quality metrics. Reactivity relies on the percentage of fresh values in the link history. Our goal is to adapt the history size on the basis of the current link quality in order to make the transmission scheme more reactive with improved estimation. Two algorithms were used to adapt the history size, one reduces the history size while the other increases it.

6.3.1 Reducing History Size

The reactivity and accuracy of the estimation metrics depend upon the percentage of fresh values in the link history. When the quality of a link is altered, the value of g is reduced and as a response, the percentage of fresh values is decreased in the link history. Suppose, the current history size 'HS_t' is 100 packets and the values of g and b based on HS_t are 20 and 15 respectively. This means that for the next estimation round only 20% of fresh values are available that show the consequences of the accuracy of link quality metrics. After transmitting 20 packets in burst, assume that the packet success rate (PSR) is greater than some predefined threshold (i.e 90% in our experiments) which depicts the accuracy of transmission metrics. For this reason, the history size will remain the same for the next round. Conversely, if the PSR is less than the desired threshold, it signifies that, the burst size obtained from the current

HS_t, does not represent the true channel condition. At this point, the HS_t is reduced to half by removing old values hence, giving more weight to the fresh values for the next prediction round.

A summary of reducing history size algorithm is given in algorithms 2. Where HS_t refers to current history size, HS_{max} refers to the the maximum history size (which is 100 packets in our experiments), HS_{min} refers to the minimum history size (which is 25 packets in our experiments) and HS_{t+1} is the future history size[ZW17].

Algorithm 2 History Size Reduction Algorithm

Input:HS$_t$, $HS_{max}, HS_{min} Output : HS_{t+1}$
if $(PSR \leq Threshold)$ **then**
  if $HS_t \neq HS_{min}$ **then**
    $HS_{t+1} = \frac{HS_t}{2}$
  else
    $HS_{t+1} = HS_t$
  end
end

6.3.2 Increasing History Size

In case the link quality is disrupted, our scheme reduces the history size which makes our estimator more reactive to the abrupt changes in link quality. Once the link quality improves and the link stability increases, our scheme increases the history size which results in: 1) reduceing the frequent link estimation 2) increasing channel statistics and 3) reducing prediction error.

Suppose, the current channel condition is poor which means the current history size is equal to a minimum 'HS_t=HS_{min}'. As soon as the channel quality improves, the value of g will increase and the maximum value it can attain is 25(packets) as HS_{min}=25 (packets). When the size of g is equal to the current history size and ($PSR > 90\%$), the new history size grows to be twice the size of the current history size. Otherwise, the channel history remains unchanged for the next round of estimation. Algorithm 3 explains the expansion of history size in detail[ZW17]:

Algorithm 3 History Size Increasing Algorithm

Input:$\text{HS}_t, HS_{max}, HS_{min} Output: HS_{t+1}$

if $(PSR \geq Threshold)$ **then**
  if $(CS == HS_t$ && $HS_t \neq HS_{max})$ **then**
    $HS_{t+1} = HS_t * 2$
  else
    $HS_{t+1} = HS_t$
  end
end

6.4 Low-Power Burst Transmission

This section propose the design of the ABT model (a sender-initiated protocol) that aims to improve throughput together with radio duty-cycling in low-power mobile wireless sensor networks(MWSNs) by allowing the sender to transmit packets in burst. The ABT model is specifically designed to support bulk data transfer in the presence of highly dynamic links. The ABT model supports the low-power burst transmission of packets i.e the ABT sender transmits packets in rapid succession after acquiring the channel in a single wakeup. Clear channel assessment (CCA) is performed only before starting a burst but not for each single packet during a burst. Two pieces of information are added in the data: an ACK packet that is g and packet number (PN). g and PN values indicate the arrival of further packets to the receiver so that it remains in the receiving mode for the upcoming packets.

6.4.1 Inter-Burst Sleeping

The ABT model takes input from the link quality component discussed in section 6.2 and accordingly allows the sender and receiver's radio to be switched off during the poor channel quality. The sender embeds the information of the current values of g, b, and PN in the data packet. The main idea here is that a sender and a receiver should go to sleep (transient-sleep) at the end of the current g and should wake up exactly before the start of the next g. Upon receiving the value of g, the receiver is updated regarding the expected number of packets to be received before going to sleep. Similarly, from b and inter packet interval (IPI) values, the receiver knows its exact sleep duration. As soon as the receiver switches to transient-sleep mode

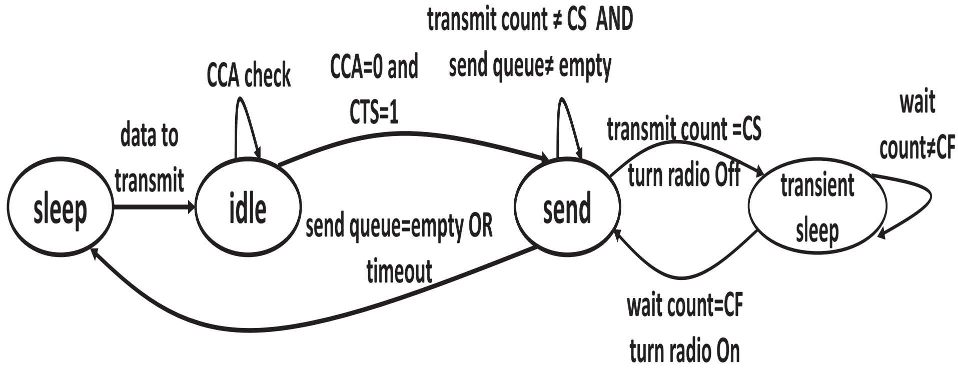


Figure 6.2: State Diagram of Primary Sender.

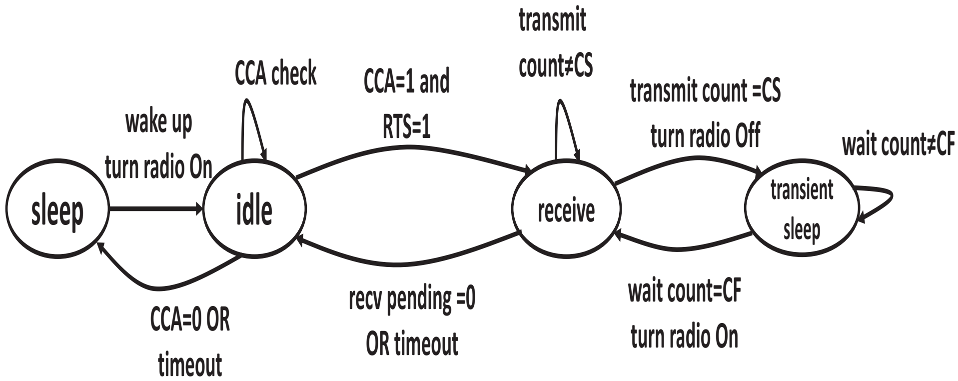


Figure 6.3: State Diagram of Receiver.

it starts a wakeup-timer which is fired exactly at the end of b. Figures 6.2 and 6.3 describe the state diagram of primary sender and receiver node respectively.

6.4.2 Inter-Burst Forwarding

The ABT protocol provides the opportunity for relay and overhearing sender nodes to transmit their data during the pause period of the primary sender. This approach enhances channel use and enables high throughput. An example of this behaviour can be seen when the receiving node is not the final destination of the current burst transmission and acts as a relay node. The relay node can utilize the b period to transmit the packet to the next hop. Relay nodes transmit packet-by-packet and perform a clear channel assessment and backoff (C&B) between each packet transmission. The reason to perform a CCA between each packet is to let other nodes to use the b period as well. Assume that during the burst transmission of one mobile node another mobile node wakes-up. As a response to overhearing the data or the ACK packet, it will go to sleep immediately for the remaining period of g. It will wake-up after a period of g

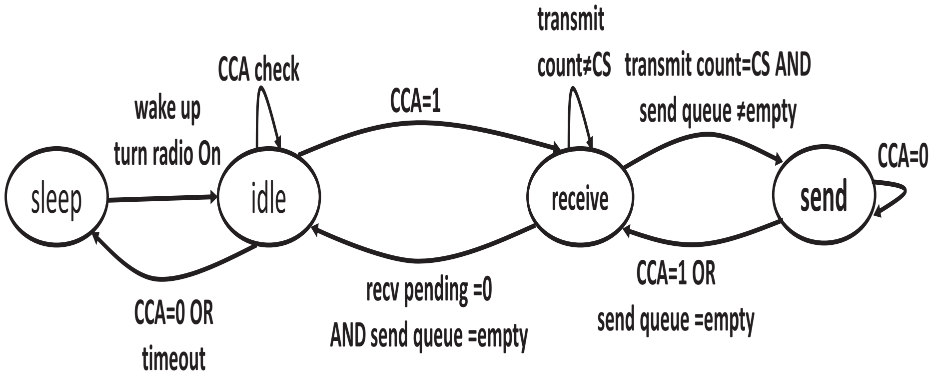


Figure 6.4: State Diagram of Relay Node.

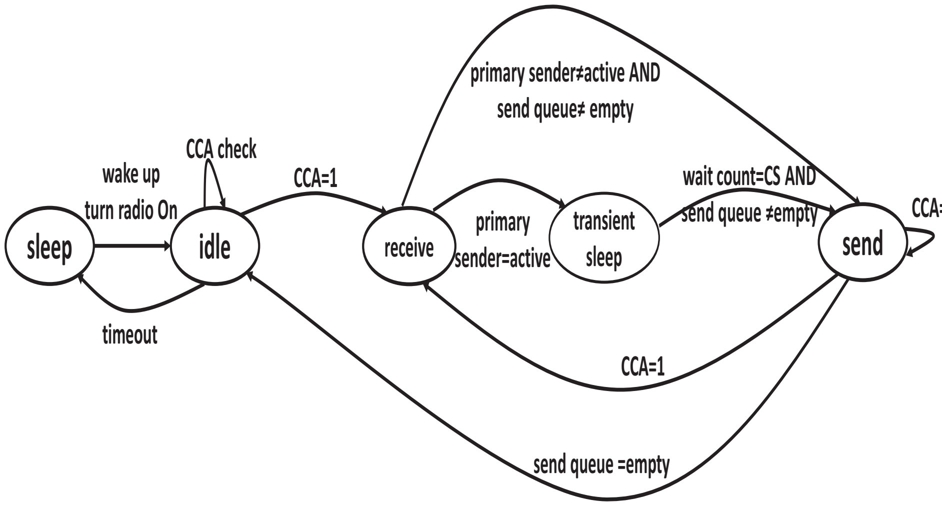


Figure 6.5: State Diagram of Secondary Sender.

in order to transmit its packets and contend with the relay node by performing C&B between each packet. Figure 6.4 and 6.5 describe the state diagram of relay and secondary sender node, respectively.

6.5 Protocol

The burst transmission scheme discussed in the previous sections 6.2 and 6.3 enables a single transmitter to efficiently use a link with a fluctuating quality. It does not, however, address (1) how the transmitter should coexist with other contending nodes which also wish to occupy the medium and transfer data, nor does it address (2) how the medium can be shared in an efficient manner.

In order to address these issues, we divide time into spans. The duration of a span is determined by the buffer size and the communication bandwidth of the relay node. In a single span a single mobile node becomes a primary transmitter and all other contending nodes become secondary transmitters. If there is no mobile node in the two-hop neighbourhood of a relay node, then the relay node itself becomes a primary transmitter and transfers the data it accumulates in its buffer to the base station. The reason we give priority to mobile transmitters is due to the unreliability of the link they establish with a static relay node. In a single span a mobile node first transmits N number of packets in burst to determine the channel statistics and the expected durations of good and bad links (by applying Equations 6.1 and 6.2). Based on this knowledge, ABT defines its duty cycle. Now its active time corresponds with the short term good state in which it transmits packets in burst. Likewise, its sleep state corresponds to its short term bad states during which time it sleeps to save energy.

To provide fairness between a mobile sender's node and the limitation of RAM storage in the Telosb(10KB) sensor node, the maximum number of packets a sender can transmit is 250 packets. In our implementation, every packet consumes 28 bytes in RAM, ultimately consuming 6.8KB of memory. The transmission time (TT) can be obtained by multiplying IPI with the total number of packets. In our experiments TT=5sec. After this time a node should vacate the channel and again compete for the channel. TT is further divided into 'n' $T_p s$ and each T_p contains T_B and T_P, where T_B is the time to transmit g packets and T_P is the pause-time before transmitting again. After each T_p the history array is updated with new values to calculate new g and b.

In the beginning, a mobile sender MS_1 wakes-up and performs C&B. If the channel is free it will send the RTS to the receiver. Upon receiving the RTS, the receiver checks its flag for the mobile sender. If no other mobile sender is active it will send the CTS and set the mobile sender flag to active. Once the mobile sender receives the CTS it will start to transmit packets in burst (Case 1 Figure 6.6). The RTS/CTS message solves hidden terminal problems and detects the transient sleep period of the mobile sender which will be discussed shortly in (Case 4 Figure 6.6).

After T_B, MS_1 will switch off its radio and go into transient-sleep, whereas the relay node (R) uses this opportunity to start transmitting the packets to the base station (BS). ABT assume the base station to have an "always-On" mode as it power by the laptop. In order to reduce

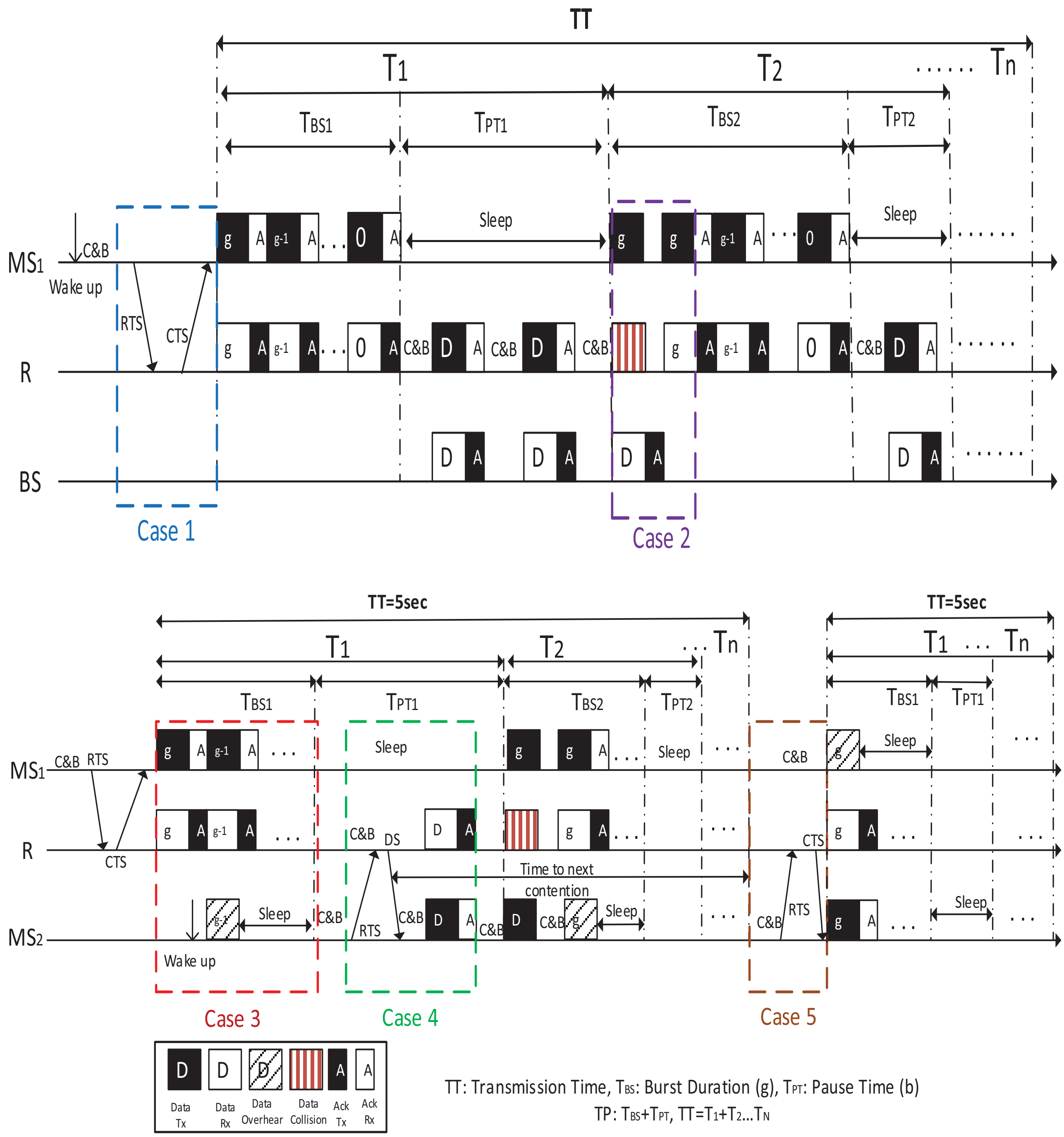


Figure 6.6: An Illustration of the Accommodation of Primary and Secondary Transmitters. Top: A relay node exploits the sleep period of a mobile transmitter to transfer packets it accumulates in its buffer to the next hop in the direction of the base station. Bottom: A mobile, secondary transmitter exploits the sleep period of a primary transmitter and transfers packets to a relay node on packet-by-packet basis.

information overhead the value of b is not included in the data packet due to which 'R' does not know the exact wake-up time of MS_1. Therefore, there might be a chance of collision between first packet after the T_p period. All the same, the probability of this is very low as R performs C&B before transmitting each packet. In case of a collision, MS_1 will retransmit the packet as illustrated in Case 2 figure 6.6.

Suppose MS_2 is woken up during the burst transmission of MS_1 and overhears the data packet which contains current burstsize g of MS_1. This inform the contending node about the on-going burst transmission and let the contender MS_2 to sleep for the remaining period of T_B (Case 3 Figure 6.6). After T_B, MS_2 wakes-up and again tries to acquire the medium by performing C&B. Discovering that the channel is now free. This is possible due to two possibilities (i) either the channel is free because TT of MS_1 is over or (ii) the channel is free because MS_1 is in transient-sleep. As MS_2 does not know the exact reason, it assumes that the channel is free and sends its RTS to the 'R'. In reality, however, this is not true as MS_1 is in transient-sleep mode. As 'R' knows the true status of MS_1 it will reply with a 'DS' message which contains the total remaining time of MS_1. After this time, the channel is free to start burst transmission. Since the total time to occupy the channel is fixed for each mobile sender after which the senders need to contend the medium again. Therefore, after sending the CTS, the receiver starts a timer for the time remaining for current burst transmission. It sends the secondary sender, the value of this timer if it receive the RTS before the expiration of the timer. Upon receiving a 'DS' message MS_2 knows the time for the next contention. Although MS_2 cannot start burst transmission, it can still send its packet to 'R' by performing a packet-by-packet transmission (Case 4 Figure 6.6). Once the TT of MS_1 is over, MS_1 and MS_2 can contend for the medium again but this time MS_1 has larger random-backoff which gives priority to MS_2 (Case 5 Figure 6.6)[ZW17].

6.6 Implementation and Evaluation

6.6.1 Implementation

I implemented the proposed protocol namely ABT in TinyOS platform and deployed it onto the TelosB sensor nodes. Additionally, two state-of-the-art protocols were also used to make

Table 6.1: A Summary of the Network Parameters used in our Experiment Setups.

Environment	lobby, lab
Mobility Pattern	Random Walk
Speed	1.3 - 2 m/s
Interferer	Microwave oven, WiFi
Overall transmitted packets	200,000
Inter-packet transmission interval	20 ms, 100 ms (lab)
Transmission power	-15 dBm
Packet payload	28 Byte

a quantitative comparison. The first is the Burst Forwarding (BF) protocol developed at the Swedish Institute of Computer Science [SOFA11], in which retransmission of lost packets due to link quality deterioration is set to 4, as suggested in their paper. The second protocol is Bursty Link Estimator (labelled as MAC_3) [AWK+11]. The MAC_3 first begins by transmitting 100 packets in burst and uses the history of the ACK packets in order to determine the size of the next burst transmission. After each transmission period, a new acknowledgement sequence is added into the link history and the burst size for the next transmission is re-estimated. In contrast, the ABT uses an adaptive history array according to the current link quality as explained in Section 6.3.

6.6.2 Evaluation

To evaluate the performance of the ABT, three sets of experiments were conducted. In the first set, the efficiency of burst transmission schemes in a single-hop network were compared under interference and in mobility scenarios. In the second set, the throughput and delay of the ABT was measured for a multi-hop network in the presence of a WiFi interferer. For these experiments, eight static nodes and one mobile node were used to set a 7-hop network. In the last set, end-to-end latency and packet loss rate was measured when multiple mobile transmitters compete to transfer data simultaneously. For these experiments, the network consist of eight static nodes and five mobile nodes. Random-walk mobility pattern was followed by all the mobile nodes. The network was deployed both in the building lobby and in lab (for the lab deployments, Yokogawa digital power analysers were used to measure the energy consumption). Figure. 6.7 shows the network topology and table 6.1 summarises the experiment parameters use in the experiments.

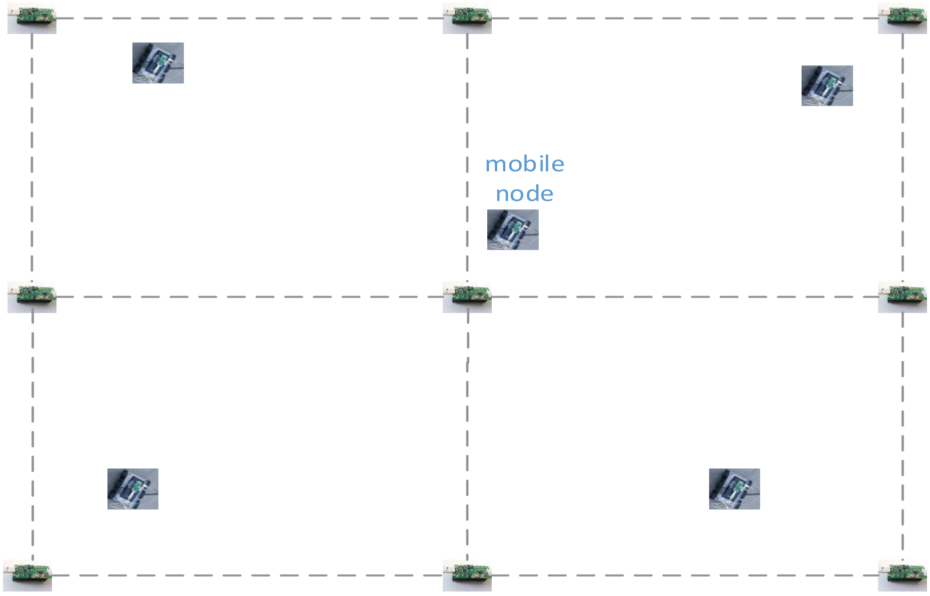


Figure 6.7: The Network Topology for One of the Experiment Sets.

6.6.2.1 Burst Forwarding

In order to evaluate the impact of Cross Technology Interference (CTI) on burst transmission two interference sources were considered, namely, a microwave oven and WiFi. For the former, we imitated [ATC+11], and [AHS14], employing a nearby Siemens HF12M240 residential microwave oven heating water during communication. In addition, the TP-Link TL-WR841N router complying with IEEE 802.11 b/g/n in the 2.4GHz ISM band was employed. This router communicated with a nearby mobile device while communication between the sensor nodes took place. The router was configured to use channel 11 while TelosB sensor nodes were allocated channel 24 which overlapped with the WiFi channel 11.

Figure. 6.8 compares the throughput of the three burst transmission schemes. A total of 5,000 packets were transmitted in each experiment and each bar graph represents the average throughput of 10 independent experiments. During each experiment, the microwave oven generates a periodic interference of shorter durations whilst a communication lasts. We observed a small number of consecutive losses (8-10 packets), but occasionally the number was larger. Subsequently, all the schemes yield comparatively similar results. However, the interference pattern produced by the WiFi router was irregular, resulting in significant consecutive losses. For this case the ABT approach produced the highest throughput, clearly justifying the need to estimate link quality fluctuation with a fresh set of ACK packets. In contrast, the BF stops

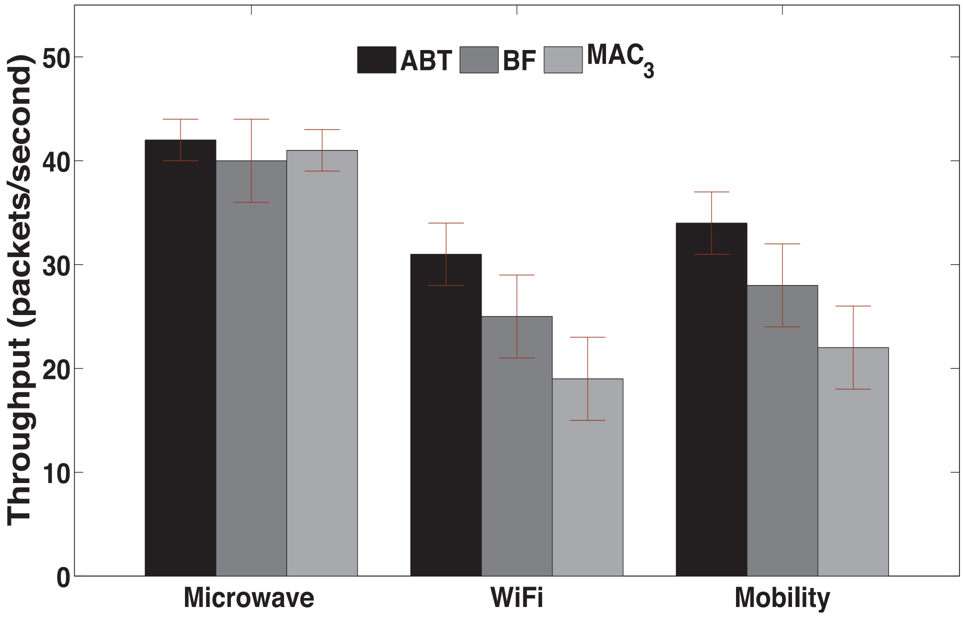


Figure 6.8: The Throughput of the Sender.

burst transmission after 4 consecutive losses and performs random back-offs (signifying a random delay of bust transmission) resulting in poor channel use. The assumption that after a loss of 4 consecutive packets the channel should be regarded as unreliable apparently yields a poor reaction time in a highly dynamic link. The MAC_3 has the longest reaction time for short-term fluctuations given that its history size is fixed. Moreover, even for a longer observation period, the expected burst size for the MAC_3 is comparatively small (between 6 to 10 packets per burst). Due to this small burst size, the history array often contains outdated data and as a result, the future burst size is often incorrectly estimated. The packet transmission time (or delay) is another way of looking at the throughput. It refers to the time required to successfully transfer a fixed number of packets (i.e., lost packets were retransmitted).

Figure. 6.9 displays the time required to transmit 5000 packets successfully. The lost packets are retransmitted by each protocol. The MAC_3 has the highest transmission time because it is slower to recover from poor channel quality, resulting in waste of the good link quality duration. The BF has the second highest delay due to employing increasing back-off mechanisms. This delays packet transmission for a longer period of time upon encountering short-term link fluctuation. The ABT has the lowest transmission delay due to its ability to adapt the burst transmission size according to the underlying quality. This is also due to the fast recovery mechanism used to detect the change in link quality, from poor to good.

To measure the energy consumption of the sensor nodes, the testbed is moved to the lab where

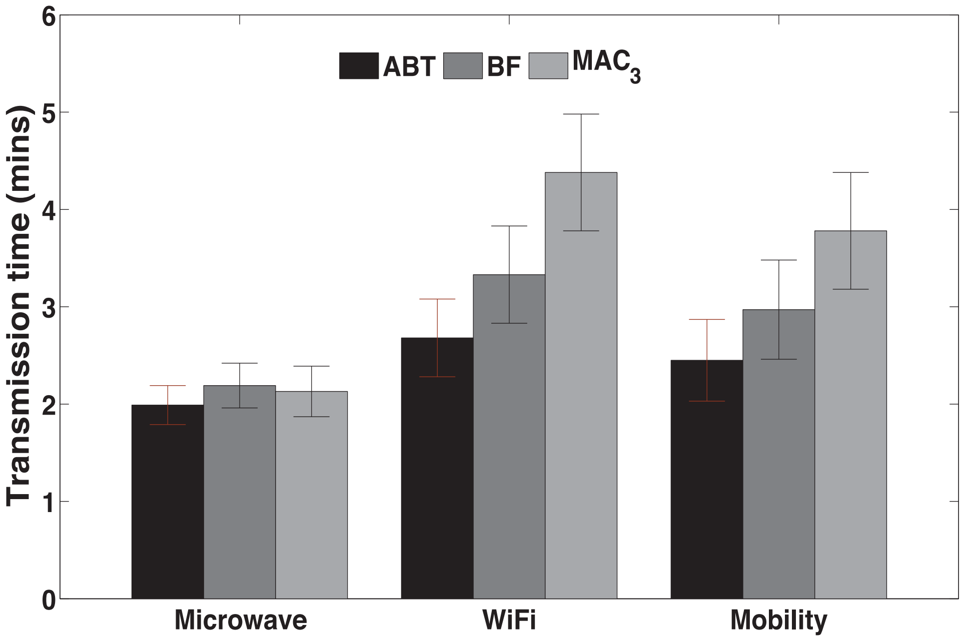


Figure 6.9: Overall Packet Transmission Time.

Yokogawa digital power analyser (WT210) is employed. All the transmission schemes used the same transmission configurations and delivered 5000 packets successfully. The maximum sampling rate the power analysers could support was 10 samples per second (i.e., a minimum of 100 ms interval between samples was required). Therefore, in order to match the power sampling frequency with the power consumption of the transmitting nodes, the inter-packet-interval (IPI) was fixed to 100 ms. Figure. 6.10 shows the actual energy consumption in watts-hour. The transmission scheme which resulted in the highest amount of energy consumption was the MAC_3. The next was the BF, because it has the longer transmission delay. The ABT resulted in the least amount of energy consumed in both cases. This was in accordance with the results observed during the evaluation of throughput and transmission delay.

In summary, compared to the state-of-the-art approaches, we observed an improvement of 2% to 4% (with the microwave setting), 24% to 34% (with WiFi), 26 to 36% (with mobility) in throughput and a reduction of 4% to 7% (microwave), 30% to 38% (WiFi) and 33% to 42% (mobility) in energy consumption with an adaptive burst transmission strategy.

6.6.2.2 Burst Transmission during Mobility

In this scenario, the predominant traffic originated from a single mobile node which had to transfer 5,000 packets in each experiment. Figure. 6.8 provides a comparison of the throughput

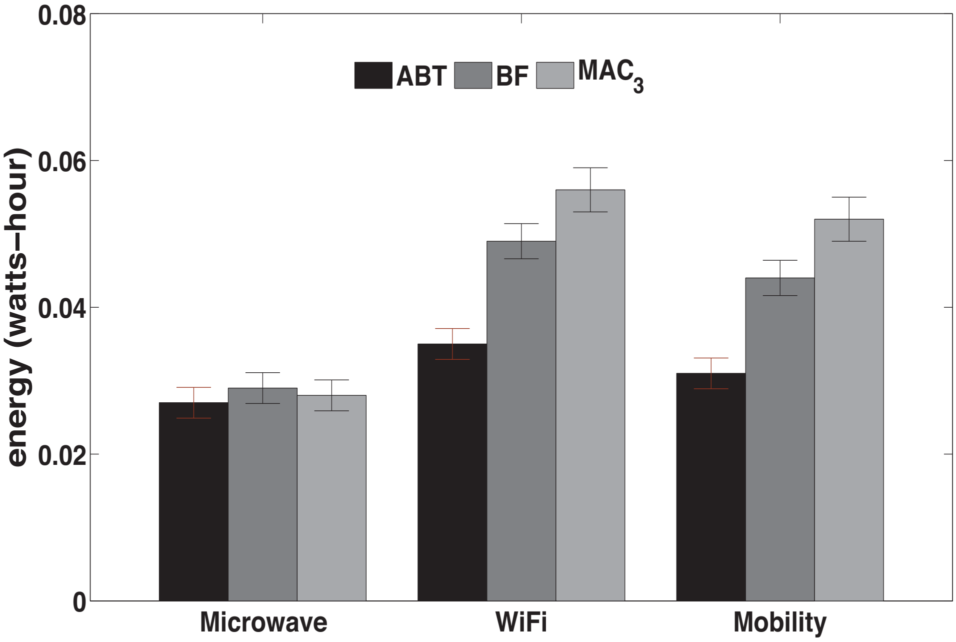


Figure 6.10: The Energy Consumption of the Transmitter.

of the three burst transmission schemes. As can be seen, the ABT has the highest throughput, the lowest delay (Fig. 6.9) and the least amount of energy consumption (Figure. 6.10). The reason behind this is that the ABT deals with short-term link quality fluctuations by adapting its history size and updating the expected consecutive successes and consecutive failures (stable link duration) accordingly. All the others techniques offer fixed solutions as they were originally intended for static networks.

6.6.3 Burst Transmissions in Multi-hop Scenarios

Multi-hop communication is unavoidable if the mobile nodes have to cover a large area. Needless to say, the performance of multi-hop networks heavily depends on the reliability of individual links and the size of local buffers. As can be seen in Fig. 6.11, our experimental setup consisted of 8 TelosB nodes comprising a linear topology to form a 7-hop wireless path. A nearby WiFi interferer was placed next to the network that supported a video download.

A mobile node at one end transmitted packets in burst to a fixed destination node. We set the TT (see Figure. 6.6) such that a maximum of 250 packets could be transmitted in a single burst. Each node on the path used a fixed time slots for burst transmission after which the mobile node would go to sleep until the beginning of the next epoch. The epoch time (t_e) was calculated as:

$$t_e = (R_n + 1) \times TT \tag{6.3}$$

where R_n is the total number of relay nodes.

We first compared the throughput of the ABT with a Baseline approach. In the Baseline approach a sender does not have knowledge of link quality fluctuation and transmits packets in burst for the entire duration of the TT. Figure. 6.12 shows the comparison between the Baseline approach and our approach by looking at the throughput of the mobile node for different hop counts. As the hop count increased the throughput decreased for both schemes. This was expected due to the increment of packet loss. Nonetheless, in the case of the ABT, the throughput is not significantly affected since the protocol stopped transmitting packets during the period of high packet losses and since it distributed this information to the forwarding nodes. The forwarding nodes, in turn, effectively used the stop period of the primary sender and transmitted the packets that were are already accumulated in their queue to the next hop. This not only increased the throughput of the network but also reduced the packet loss and minimised the retransmission cost.

Altogether we transmitted 5000 packets with each hop count using both the Baseline model and our approach. We measured the overall packet transmission time to successfully deliver all the packets. Figure. 6.13 shows the transmission time with each hop count. The ABT has the lowest transmission time in comparison to the Baseline approach.

In summary, by comparing ABT to the Baseline approach, we are able to observe an improvement of 20% to 40% throughput with our adaptive transmission strategy.

6.6.4 The Co-existence of Multiple Transmitters in a Multi-hop Network

In the last set of experiments, multiple mobile transmitters contend to transfer bulk-data to a fixed sink via multiple relay nodes. In a network which supports all mobile nodes impartially, a single node should not monopolise the available channel indefinitely. Therefore, the idea of bulk-data transfer should not contradict the idea of fairness. Figure. 6.14 shows the

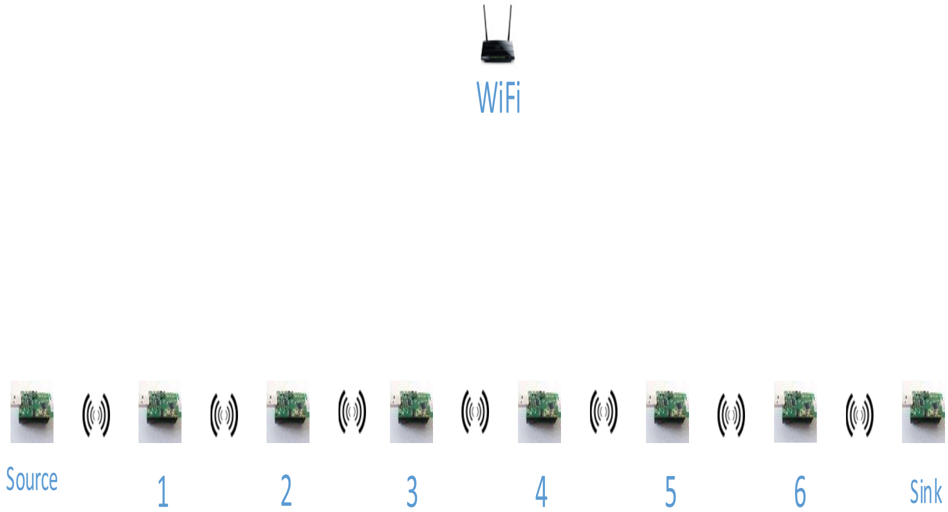


Figure 6.11: Multi-hop Sensor Network

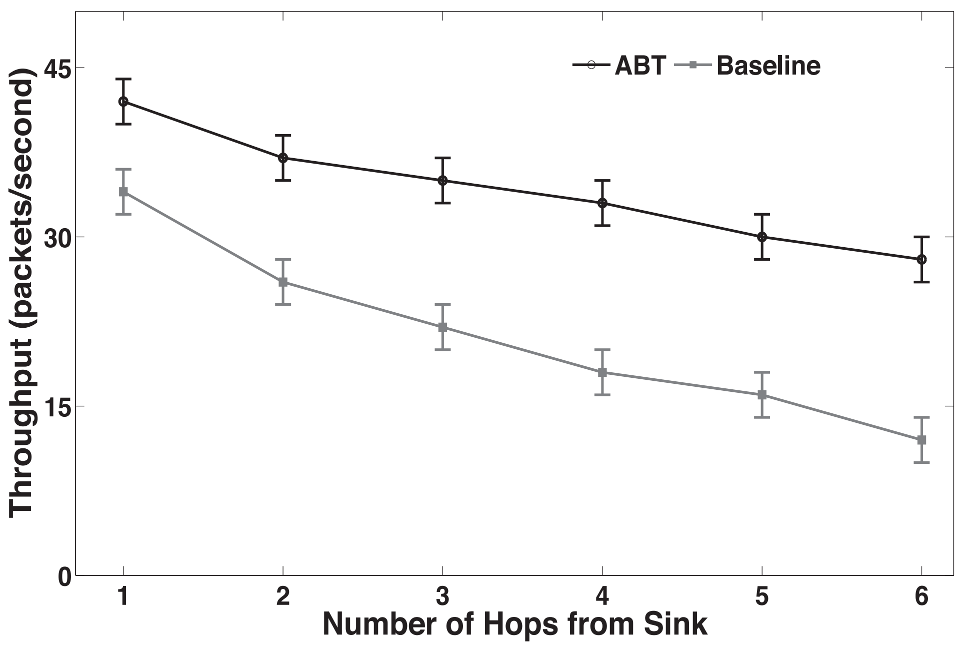


Figure 6.12: The Throughput for Different Number of Hops.

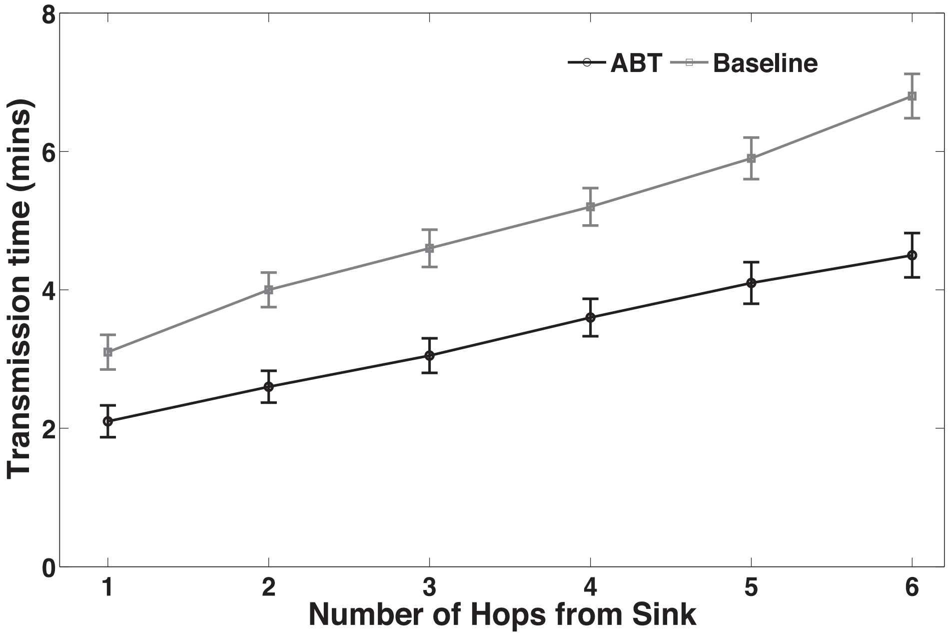


Figure 6.13: The Transmission Time for Different Number of Hops.

average end-to-end delay for number of different mobile transmitters. As the number of mobile transmitters increases, the delay increases linearly for obvious reasons. But with the ABT, secondary transmitters could use the channel during the intermediate stop period of the primary transmitter. This reduces the end-to-end latency for each mobile transmitter, as evident in figure. 6.14(a).

Similarly, figure. 6.15 compares the end-to-end packet loss rate of each transmitter using two approaches. The ABT has the lowest packet loss rate of all the transmitters due to its online link quality estimation. The Baseline approach did not estimate the underlying link quality which transmitted packets even during a bad quality duration resulting in a high packet loss on some links, this loss was as high as 80%. The ABT efficiently adapted the packet transmission based on the adaptive link quality estimation, resulting in reduction of the packet loss rate.

In summary, the ABT achieved a reduction of 20% to 52% end-to-end delay as compared with the Baseline approach. It reduced its packet loss by 14% to 48%.

6.7 Summary

Mobility has a high impact on link quality fluctuation and most of the protocols in sensor networks focus only on bulk transmission and do not address issues related to the time-varying

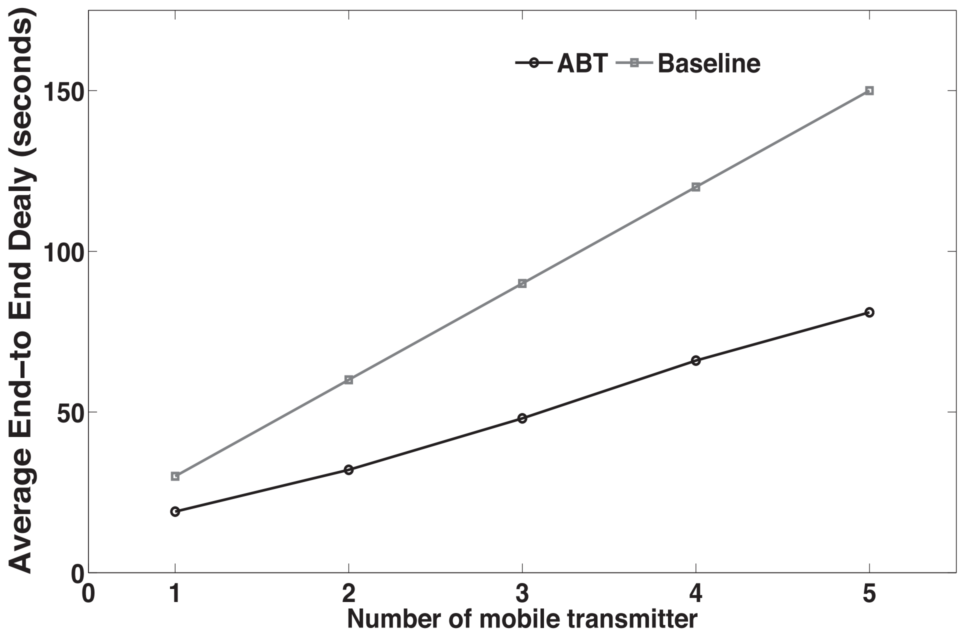


Figure 6.14: Average End-to-end Delay in a Multiple Transmitter Multi-hop Scenario.

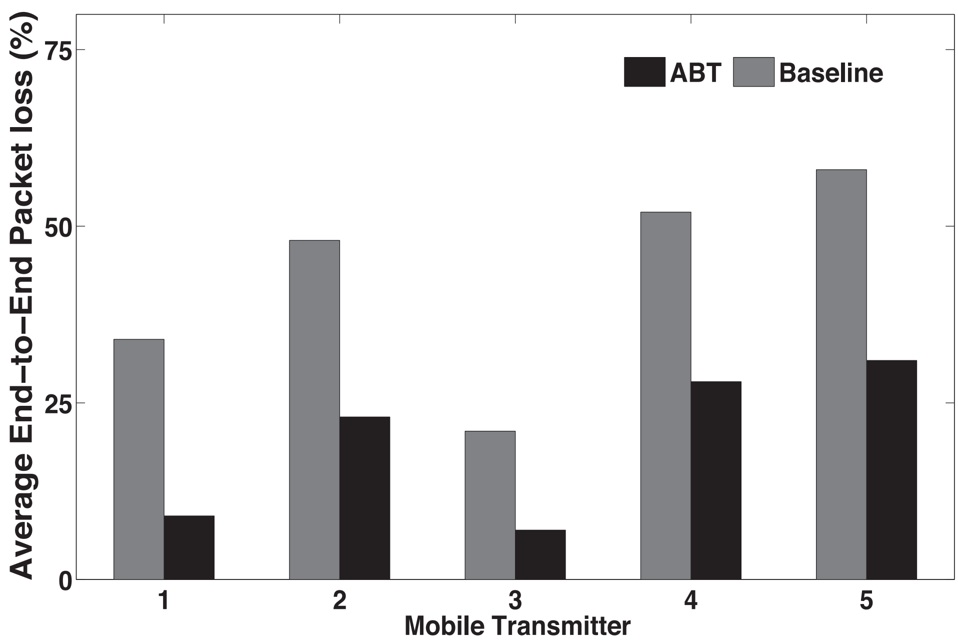


Figure 6.15: Average End-to-end Packet Loss Rate in a Multiple Transmitter Multi-hop Scenario.

characteristics of the wireless channel. As a result, they suffer from high packet loss and high energy waste. In contrast, our work in this chapter, not only focused on providing a high throughput but also on providing duty-cycle (by setting nodes up to sleep during poor channel conditions). Our approach enables the MAC protocol to learn the channel characteristics, adapt quickly, and schedule packet transmission accordingly.

This chapter proposed an adaptive burst transmission (ABT) protocol to provide high throughput and adaptive duty-cycles in wireless sensor networks which accommodate mobile nodes. The ABT deals with link fluctuation by estimating the durations of good and bad states from the statistics of incoming ACK packets. The ABT also adapts the size of the history array to improve the quality of the prediction. Each node in the ABT adapts its duty-cycle based on its traffic flow and underlying link quality. Furthermore, the ABT enables neighbour nodes to share information pertaining to link states and, thereby, to achieve better channel use.

To evaluate the performance of ABT protocol with the state-of-the-art approaches, the ABT, the BF and the MAC_3 are implemented in TinyOS and deployed on TelosB sensor nodes. Extensive experiments are performed in a multi-hop mobile wireless sensor network. The aim of these experiments is to compare throughput and end-to-end latency in a mobility enabled multi-hop wireless sensor networks. The result of the experiments conclude that the ABT was able to achieve a higher throughput, minimum packet transmission time, and less energy consumption in the existence of significant interference and mobility.

In comparison to the state-of-the-art approaches, the ABT improves the throughput upto 4% (with the microwave setting), upto 34% (with WiFi), and upto 36% (with mobility) and reduces energy consumption upto 7% (microwave), upto 38% (WiFi) and upto 42% (mobility). The corresponding cost is an intensive background computation to update the system's beliefs pertaining to the expected duration of good and bad states. Also, in a multi-hop scenario, the ABT is able to improve throughput upto 40% due to efficiently using channel capacity by sharing link quality information. Similarly, in multiple transmitter scenario the ABT reduce end-to-end delay upto 52% and packet loss upto 48% compared to the Baseline approach. The reason for this being its adaptive and efficient link estimation strategy. Moreover, ABT showed that by sharing link quality information, the average throughput of the network could be improved and end-to-end latency could be reduced in a multi-hop network. The ABT is easily integrable with existing or proposed MAC protocols and complies with the existing IEEE 802.15.4 specification.

We believe that the ABT can leverage routing and transport layer protocols to further improve energy efficiency under interference and mobility.

Chapter 7

Comparison of the Proposed Approaches

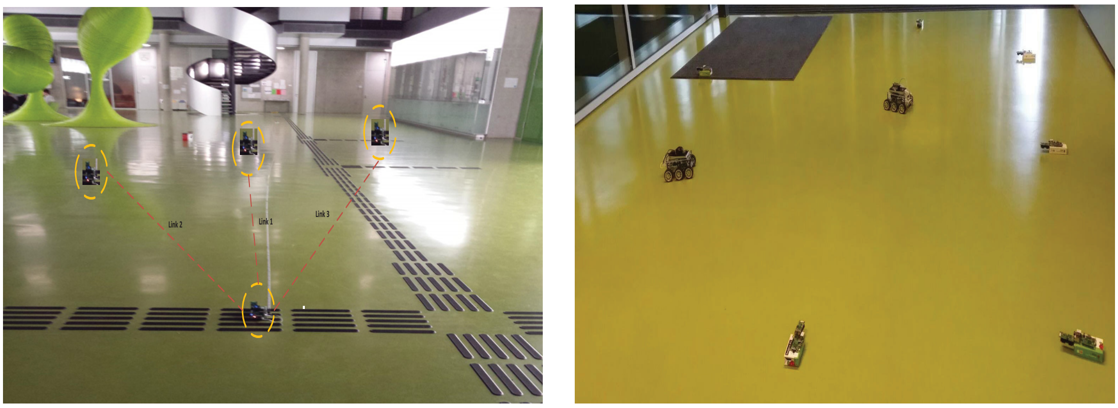
To compare and validate the performance of the proposed approaches in this thesis extensive experiments were performed by laying a testbed in different environments. The performance of offline, online, and hybrid approaches are compared using performance metrics packet success rate, throughput, and energy consumption. The hybrid and online approaches 'H-DMB' and 'ABT' respectively, are implemented and integrated in the TinyOS for TelosB platform. However, for the offline approach 'DMB', evaluated results are uploaded in TelosB nodes using a look-up table to schedule packets for communication in real-time. The ability to model different variations by all the proposed schemes in both static and mobile environments are compared with the limitation of each scheme clearly defined.

7.1 Transmission Parameters and Network Topology

To establish links with different quality transmission parameters such as transmission power, distance between the transceivers and inter-packet-interval are used. Table 7.1 summarises some of the parameters that are included in the experimental set up. I did not use low-power listening MAC and routing protocols as optimising duty-cycle and multi-hop communication was not the focus of these experiments. More than 1 million packets were transmitted for modelling and performance evaluation. For managing and logging data successfully into a sensor node memory,

Location	Lobby
Overall transmitted packets	1.2 million
Inter-packet transmission interval	20,100 ms
Transmission power	-25,-15,-10 dBm
Distance	5 to 50 m
Mobility Pattern	Straight line Walk, Random Walk
Speed	1.0-2.5 m/s
Packet size	28 Byte

Table 7.1: Parameters Defined for the Experiments to Evaluate the Performance of Three Proposed Schemes.



(a) Static lobby deployment (b) Mobile lobby deployment

Figure 7.1: Network Topology

a 20 ms inter-packet interval (IPI) was inserted between each packet during the transmission of packets in burst. Each experiment was performed 10 times to remove radio irregularity. Figure 7.1 shows the network setup used to conduct the experiments.

7.2 Static Scenario

The testbed was deployed in the lobby of the Andreas Pfitzmann Bau. The network consists of three pairs of transmitters and receivers forming three different link qualities. Figure 7.1(a) shows the experimental setup of static deployment. The parameters used to establish these links are summarised in Table 7.2. Out of all the parameters mentioned, transmission power and distance between the transceivers most affect the quality of link.

	Link1	Link2	Link3
Distance (m)	8	19	35
Power (dBm)	-25	-15	-10
Location	Indoor	Indoor	Indoor
IPI (ms)	20	20	20

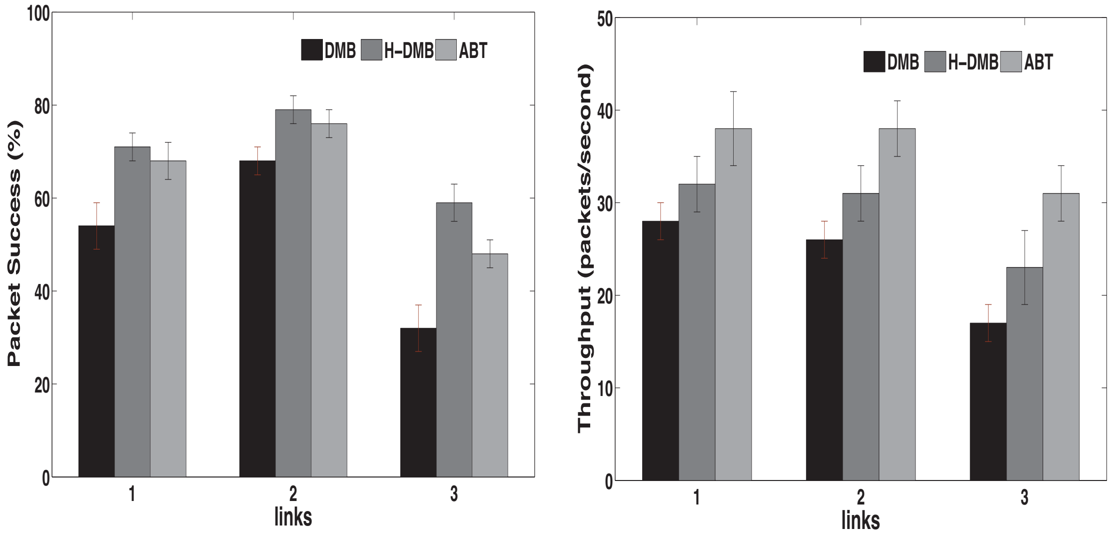
Table 7.2: A Summary of Physical Parameters Used to Establish the Links.

7.2.1 Packet Success Rate and Throughput

To compare the efficiency of all the proposed models, the packet success rate is measured on three links, as shown in figure 7.2(a). Each scheme transmitted 5000 packets successfully on each link and the experiments were repeated 10 times. The hybrid scheme H-DMB has the highest packet success rate on all the links because because of how efficiently it estimates correct burst size. The H-DMB approach models long-term link quality fluctuations in an offline phase to determine the size of burst. It is supported by real-time feedback in an online phase to deal with short-term link quality fluctuations, hence resulting in a higher packet success rate. The DMB model has the lowest packet success rate in comparison to the other two approaches. However, both DMB and H-DMB models uses the same mathematical algorithm to model link quality fluctuation. The only difference between the DMB and the H-DMB model is the real-time feedback added for the hybrid approach. This additional feature highlights the importance of dealing with short-term link quality fluctuations. The packet success rate of the ABT is 3 to 10%, less than that of the H-DMB approach because the ABT applies a fast detection strategy by transmitting a fixed number of 'n' packets in burst for a short duration during poor channel conditions. This helps detect the change in link quality from a poor to a good state. On the one side, this strategy reduces the packet success rate, but on the other side it increases the throughput as shown in figure 7.2(b). The ABT has the highest throughput on all the links where the DMB has the lowest throughput due to a fixed burst size and being unable to detect short-term link quality fluctuation. ABT achieves between 15 to 45% gain in throughput in comparison to H-DMB and DMB.

7.2.2 Energy Consumption

Energy consumption is one of the significant performance metrics used in wireless sensor networks. The Yokogawa digital power analyser (WT210) is connected to the transmitter node



(a) Packet Success Rate

(b) Throughput

Figure 7.2: A Comparison of the Packet Success Rate and Throughput of the Three Burst Transmission Approaches for Different Wireless Links in Static Scenario.

to measure energy consumption. For experimental purposes, all the proposed schemes are required to transmit 5000 packets successfully, meaning lost packets are retransmitted. Each experiment is repeated 10 times and as previously shown, an error bar is plotted. Each sender node switches off its radio during the pause time to save energy. The TelosB nodes consume 0.05 watts of power every time they transmit. Figure 7.3 shows the energy consumption of all the transmission schemes. The DMB model has the highest power consumption. H-DMB approach consumes the least amount of energy due to retransmitting the lowest number of lost packets as evident from previous results. The reason is the efficient modelling of long-term link quality fluctuation combined with real-time feedback to improve channel state prediction. The H-DMB approach improves energy consumption upto 10% in comparison to the ABT and upto 25% in comparison to the DMB method. Each sensor node switches off its radio in pause duration hence, it does not consume any energy. In fact, the node only consumes energy when it transmits the packet. The scheme that retransmits the highest number of packets consumes the most energy.

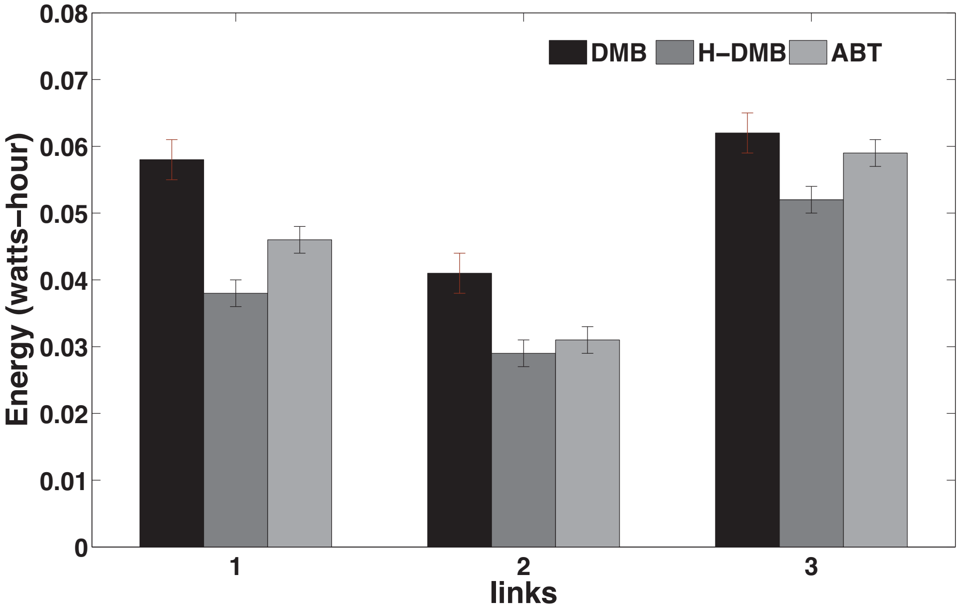


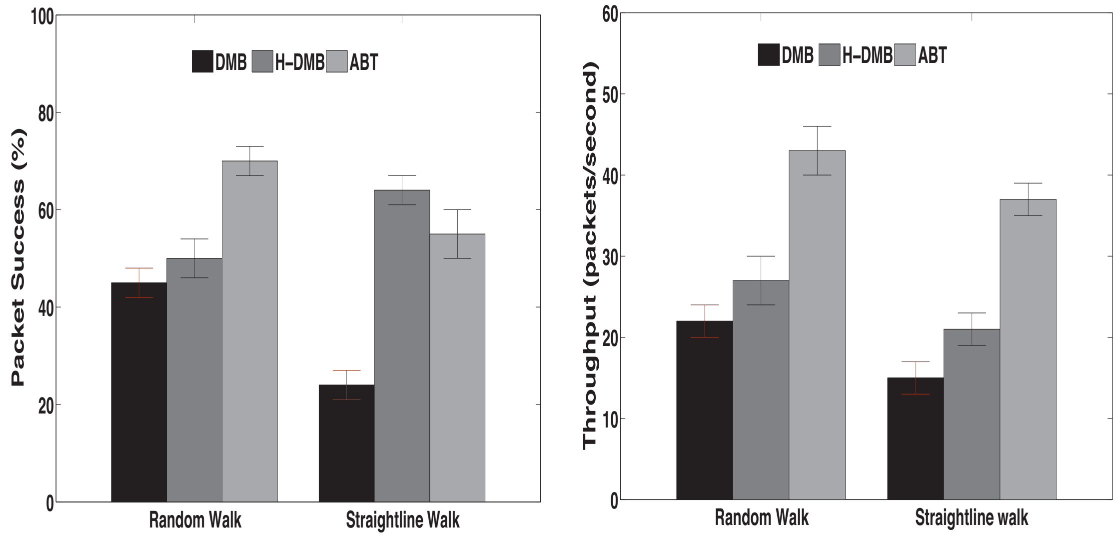
Figure 7.3: A Comparison of Energy Consumption Using the Three Burst Transmission Approaches for Different Wireless Links in a Static Scenario.

7.3 Mobile Scenario

To study the impact of mobility in wireless sensor networks, mobile nodes are deployed and figure 7.1(b) shows the experimental setup of this mobile deployment. The network consists of a mobile node carried by a human by hand. The human walks into the lobby area, the dimensions of which are 40m x 10m x 70m (length, width, height). The human follows two mobility patterns: (1) random walk: in which the human carrying a sender node walks randomly around the lobby area (2) straight line walk: in which the human carrying the sender node moves away from the receiver in a straight line until the link between them disconnects. The transmission power is set to -25 dBm for both movement patterns. Table 7.2 summarises other transmission parameters used in these experiments.

7.3.1 Packet Success Rate and Throughput

In the mobile scenario, experiments were performed with the requirement that all the schemes transmit 5000 packets successfully with each mobility pattern. Figure 7.4 shows the packet success rate and throughput of the proposed scheme with two mobility patterns. The ABT has the highest packet success rate and throughput with a random-walk mobility pattern. This is due to the efficient estimation of short-term link quality fluctuation achieved by adapting the



(a) Packet Success Rate (b) Throughput

Figure 7.4: A Comparison of the Packet Success Rate and Throughput of the Three Burst Transmission Approaches for Different Wireless Links in a Mobile Scenario.

size of the history array in real-time. While walking randomly, the mobile node stays within the connected region, thereby exhibiting short-term link quality fluctuation which is well modelled by the ABT. While following the straight line walk pattern, the mobile node moves away from the receiver until the link between them is disconnected. It then stays in this disconnected region for a random duration before entering the connected region again. Therefore, it exhibits long-to-middle-term link quality fluctuation. Figure 7.4(a) shows that the H-DMB approach has the highest packet success rate for a straight line walk due to efficient modelling of long-to-middle-term link quality in the disconnected region.

However, the ABT has the highest throughput for both mobility patterns given that it employs an adaptive burst size and quickly detect changes in link quality. The H-DMB model performs better than the DMB offline approach so far as both mobility patterns are concerned. This is due to inclusion of real-time feedback to fine-tune the offline model. The DMB has the lowest packet success rate and throughput as it relies only on the offline statistics and has no mechanism to detect the short-term changes in link quality. The ABT achieves between a 5% to 17% and a 10 to 45% gain in the packet success rate and throughput, respectively, as compared with both H-DMB and DMB approaches. However, for the straight line walk model, the H-DMB shows improvement in the packet success rate, between 4% and 12% as compared with the ABT.

7.3.2 Energy Consumption

To measure the amount of the energy consumed by the transmitting node, the sensor network is moved into a lab settings. When the sender node is attached to the power analyser, it is no longer mobile. In this case, the receiver node becomes the mobile node. To perform experiments, once again all the proposed schemes have to transmit 5000 packets successfully hence the lost packets are retransmitted and each experiment is repeated 10 times. The experiments show that the ABT has the lowest energy consumption for the random walk mobility pattern when compared with the to H-DMB and DMB models. The adaptive transmission strategy employed by the ABT results in low energy consumption. With the random walk the link quality fluctuates over a short period of time. Therefore, the ABT achieves the highest packet success rate and the lowest packet failure rate, resulting in a reduced packet retransmission, meaning it consumes the least amount of energy. The ABT has improved energy consumption of upto 30% in comparison to the H-DMB approach and upto 45% in comparison to the DMB approach using a random walk model. However, in the case of the straight line walk model, the H-DMB model consumes the least amount of energy due to its efficient modelling of the duration of the disconnected regions. Hence, it reduces the number of packets lost and consequently, the total energy consumed. The energy consumed by the H-DMB approach improves by 10% in comparison to the ABT in the case of a straight line walk model. The DMB model has the highest energy consumption rate for both mobility patterns due to a fixed transmission strategy based on offline modelling.

7.4 Summary

This chapter compares the performances of the various proposed approaches, namely the DMB, H-DMB, and ABT approaches in both static and mobile environments. All the schemes are compared using three performance metrics- packet success rate, throughput, and energy consumption.

In a static environment, the H-DMB model was found to have the highest packet success rate due to efficient estimation of both long and short-term link quality fluctuations. The DMB model has the lowest packet success rate and the highest packet loss rate due to its inability

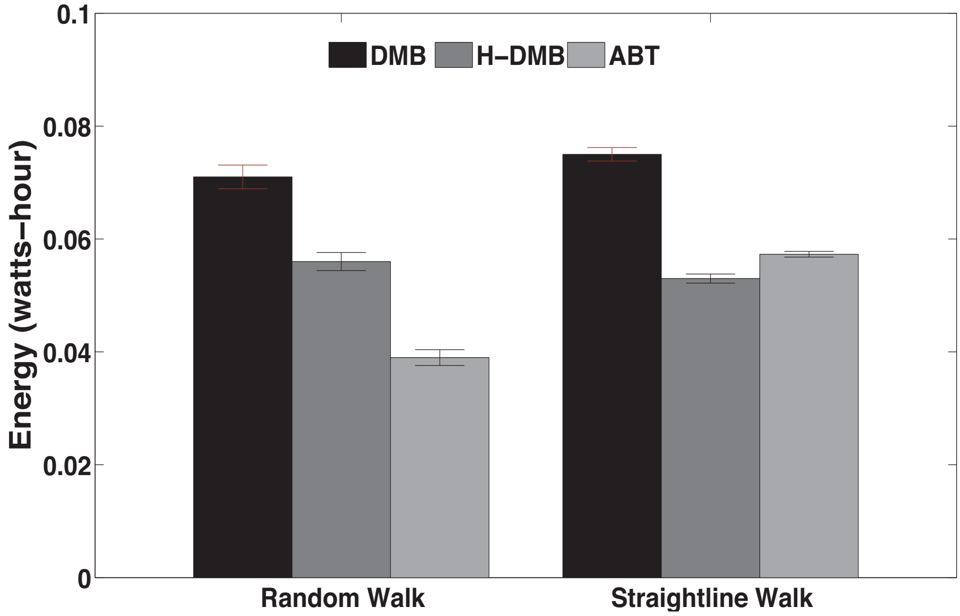


Figure 7.5: A Comparison of Energy Consumption of the Three Burst Transmission Approaches for Different Wireless Links in Mobile Scenario.

to detect short-term link quality fluctuations. The only difference between the H-DMB and the DMB is the addition of the real-time feedback system in the former. Hence, it can be concluded that an estimator which is able to deal with both long-and short-term link quality fluctuation is required. The H-DMB shows improvement in packet success rate of upto 30% as compared to the DMB model. While comparing the hybrid scheme with the ABT, the H-DMB model achieves upto a 10% gain in packet success rate. This, however, is at the cost of an increased transmission time, whereas the ABT has reduced the transmission time and increased the throughput upto 45% in comparison to the H-DMB model. The ABT improves the throughput while reducing the transmission time because of its fast link quality detection strategy and its adaptive history array.

In the case of mobility deployment, two walk models, one of which is random and the other, a straight line walk, are considered for comparison. The ABT proved to have the highest packet success rate for the random walk model. In the random walk the link quality fluctuates over a short period of time due to continuous movements and changes in antenna directions. This is captured by the ABT due to its adaptive burst size estimation in real-time. The ABT shows an improvement in the packet success rate upto 17% for the random walk model. For the straight line walk model, the H-DMB approach has the highest packet success rate. The H-DMB approach achieves upto a 12% gain in packet success when compared with the ABT. As the sensor nodes move away from the receiver in one direction, they exhibit long-term fluctuation.

However, the H-DMB model has the highest transmission delay due to the estimation errors the of CPESD.

This chapter can be concluded by stating that the offline approach models long-term link quality fluctuations and is suitable for static environments in which link quality has long-term characteristics. However, the offline model is unable to detect the short-term fluctuation in link quality. Therefore, combining the offline model with real-time feedback creates a hybrid approach which improves the reliability of packet transmission. Experimentally, it has also proved to have a considerable gain in the packet success rate with a decrease in energy consumption. However, the H-DMB approach is not suitable to model link quality in mobile environment (for random walk) where link quality fluctuates over a short period of time. To model short-term link quality fluctuations, an online approach which uses real-time data to model the burst size performs exceptionally well and has shown considerable gain experimentally. The straight line walk pattern yields long-term link fluctuations which are well modelled by the H-DMB approach and show improvement in the packet success rate. Therefore, the hybrid approach is even suitable for mobile environments where link quality shows long-to-middle term link fluctuations.

Chapter 8

Conclusion

Burst transmission is essential to meet the demands of high throughput for many applications such as healthcare, animal monitoring, and vehicle-to-vehicle communication in wireless sensor networks. Most of the existing burst/bulk transmission protocols are unaware of channel dynamics and are unable to cope with rapidly changing link conditions resulting in suboptimal channel access patterns. The quality of the radio signal deteriorates considerably in both indoor and outdoor environments due to path-loss, multi-path, fading, shadowing and mobility. Therefore, it is necessary for the burst/bulk transmission protocols to estimate the quality of wireless links in order to improve the packet success rate and energy consumption of low-power wireless network. Since link quality is highly dynamic in wireless sensor network, an adaptive link quality estimation is critical for efficient and reliable communication. This dissertation focuses to model link quality fluctuations by estimating packet success and loss correlation, caused by such factors as environment change, internal and external interference and mobility of the sensor nodes. The hybrid algorithm presented in this dissertation considers both short-and-long term link quality fluctuations.

This dissertation concludes with a brief summary of the proposed link quality models and points out what kind of work could be done in the the future.

8.1 Thesis Summary

In this thesis, I argued for the need of link quality estimation for burst/bulk transmission protocols in wireless sensor networks. The empirical study, conducted in different static and mobile environments, reveals that wireless links are bursty or in other words, packet successes and losses are correlated. Hence, to improve the performance of burst transmission protocols, I incorporate an efficient link quality estimation model with burst transmission protocols. The link quality estimation models presented in this thesis adopt probabilistic and machine learning approaches to model link quality fluctuations. In particular, the transmission scheme exploits channel correlation from the statistics of the acknowledgment packets and schedules packet transmission according to the underlying link quality fluctuations. This method of dealing with link quality fluctuation in general and link burstiness in particular, can be divided into three categories: offline, online, and hybrid. To support my argument, this dissertation proposes four models to estimate link burstiness in two different environments settings with both static and mobile arrangements. The proposal aims to increase throughput as well as to reduce packet transmission delay and energy consumption- hence, improving the overall performance of wireless sensor networks.

8.1.1 Offline Approach

The offline approach estimate long-term link quality fluctuations from large channel statistics using complex algorithms. It is thus best suited to model link quality fluctuations in static deployment. The advantage of this approach is the availability of a large data set upon which various complex algorithms of choice can be applied without the constraint of memory and computational complexity. In static deployment, the link quality fluctuation statistics can be regarded as stationary in a wide sense, in which case, it is sufficient to transmit large number of packets once, accumulate the statistics offline, determine the expected durations of good and bad states, and finally, use this knowledge to schedule packet transmission and sleep times. To learn the long-term characteristics of low-power wireless links, extensive experiments were performed in both indoor and outdoor environments. The statistics obtained from these empirical studies form the basis for the two offline approaches I designed, CPB and DMB.

The design and the implementation of Conditional Probability Based scheme (CPB) is presented in chapter 4. The CPB scheme solves the problem of long-term link quality fluctuations by applying a conditional probability distribution function. The cumulative distribution function is obtained by setting the SNR threshold on the incoming acknowledgement packets. The CPB scheme estimates the duration of a reliable and an unreliable transmission period by obtaining the expected value of the conditional cumulative distribution function. The CPB scheme first calculates the SNR value of the incoming acknowledgement packets. It then applies the SNR threshold to convert the continuous SNR function into a discrete function. The width of the obtained discrete function determines the stable period and builds the cumulative distribution function. Finally, it computes the expected value of the distribution function to calculate the reliable and unreliable period. So the important factor influencing the performance of the CPB scheme is the chosen value of the SNR threshold based on the application requirements. If the application demands high packet reliability, then a higher value of the SNR threshold must be selected. On the contrary, in order to meet high throughput requirements, it is necessary to choose a lower value of the SNR threshold. According to the IEEE 802.15.4 specification, to achieve the packet error rate of 1% of received packets, the minimum SNR value must be atleast 5-6 dB [41507]. To evaluate the performance of the CPB scheme, I compare it to the Baseline approach which does not estimate link quality fluctuation. The experiments are performed in both indoor and outdoor environments. The results show that a CPB scheme improves the packet success rate upto 40% in comparison with the Baseline. This improvement in the transmission metrics emphasises the need for estimating link quality fluctuations for burst transmission protocols.

However, the limitation of the CPB approach is that the choice of the SNR threshold is dependant on the application. Hence, no generalisations can be made about all types of links, especially for intermediate quality links with a large transitional region. In the transitional region, link quality varies considerably over a short period. Therefore, packets can be lost even with the SNR value set as high as 15 dB or more. Packets can also be successfully delivered even with an SNR value as low as 6 dB or less. Thus, the CPB approach can under-or over-estimate the quality of the link depending on the value of the SNR threshold.

To overcome this limitation of CPB scheme, a Double Markov Based (DMB) model is proposed in chapter 4 to estimate long-term channel characteristics. The DMB approach estimates the duration of reliable and unreliable periods in three steps: clustering, link state duration, and the burst size of each state. The DMB scheme describes the relationship between the signal-to-noise ratio (SNR) and the acknowledgement reception ratio (ARR) using channel statistics obtained from the pre-deployment phase. K-mean clustering is employed to divide the link quality into 'n' number of possible states. To find the optimal number of channel states that best describes the channel, the *silhouette method* is used. The optimal number of states depends on the size of the transitional region; the larger the region is, the more states are required to efficiently describe the transitional region. Once the states are known, the DMB model calculates the transitional probabilities between the states as a discrete Markov process. The probability mass function helps the DMB model to determine the expected duration of each state, the time duration over which the state of the channel does not change. Finally, a two-stage Markov model is employed for each channel state to calculate transitional probabilities, which then determines the burst size for each state. In other words, pre-determined number of packets should be transmitted in burst and similarly, a pre-calculated number of packets need to be halted before transmitting again. With this mechanism, the DMB model improves the packet success rate up to 25% in comparison to CPB approach.

The DMB and the CPB models take advantage of the assumption that if link quality fluctuation is observed for a sufficiently long time, then the statistics obtained can be considered stationary in a wide sense and the link quality can be modelled offline by employing complex machine learning algorithms. The evaluation confirms a high gain in the packet success rate and a significant decline in the packet loss rate by estimating link quality using DMB and CPB models. This highlights the importance of link quality estimators especially those which measure link burstiness for bulk/burst transmission protocols for wireless sensor networks.

8.1.2 Hybrid Approach

The hybrid approach combines the benefits of both offline and online approaches and models long-to-short term link fluctuations. Due to the limited storage and computation power of sensor nodes, complex algorithms and large channel statistics can not be used in real-time. Therefore, the idea behind the hybrid approach is to learn and model long-term link quality fluctuations using large data sets collected offline. The results of the model should then be embedded in the sensor node to use in real-time together with real-time channel feedback. Chapter 5 proposes the design of the H-DMB scheme, a hybrid approach that addresses link quality fluctuation in real-time. The H-DMB model is comprised of two phases; offline and online.

In the offline phase, long-term link quality fluctuation is modelled by DMB scheme which combines k-mean clustering and the Double Markov Model to determine the stable duration of the channel quality, already discussed in detail in chapter 4. The result obtained from the offline phase is embedded into the sensor nodes using look-up table. The Look-up table contains the number of states, the duration of each state and the burst size of each state.

In an online phase, the H-DMB model divides the transmission time into slots; the duration of each slot is fixed to 10 packets. The H-DMB model estimates the state of the channel in each slot on the basis of the incoming acknowledgement packets. If the observed state is different from the current channel state, then the H-DMB initiates the algorithm to correct the channel state by collecting enough channel statistics. Otherwise, it stays in the same channel state for the remainder of the channel state duration. The H-DMB model is designed and implemented in TinyOS platform and on TelosB sensor nodes. When compared with two state-of-the-art transmission schemes in indoor and outdoor environments, the H-DMB model showed up to a 35% improvement in throughput and transmission time. This hybrid approach also improves energy consumption up to 40% as it deals with both long-and-short term link quality fluctuations.

8.1.3 Online Approach

The online approach is designed and developed to deal with link quality fluctuations in mobile wireless sensor networks. The CPB, DMB, and the H-DMB schemes are designed to model link quality fluctuations in static environments as the modelling is based on large channel statistics obtained in the pre-deployment phase. Unlike the static environment, link quality fluctuation in mobile scenarios cannot be regarded as stationary due to unpredictable mobility patterns. Therefore, the offline channel statistics can not be used in this scenario, which is why the previously proposed models; CPB, DMB and H-DMB can not be utilized. Given that the packet transmission rate is higher in comparison to the speed of mobile node under test (the mobile node carried by humans or animals), it is possible to gather sufficient statistics in real-time to model the short-term link quality fluctuations. In chapter 6, an adaptive burst transmission (ABT) approach is proposed to estimate the duration of good and bad links on the basis of the statistics of the received ACK packets. The ABT approach also enables the coexistence of multiple transmitters during bulk-data transfer. ABT begins by calculating the probability of successfully transmitting 'n' number of packets in succession. ABT then take the expected value which describes the expected duration of a good state from a short history array. Similarly, the expected value of the probability of losing 'm' number of packets in succession describes the expected duration of a bad state. An adaptive history array helps the ABT model to improve the quality of the prediction as well as the reaction time of the transmission scheme. Prediction accuracy is highly dependent on the freshness of the value in the history array. The ABT model selects the packet success rate as the inductor for prediction accuracy. For a packet success rate of PSR< 90%, the ABT reduces the history size as a way of giving more weight to the more recent values.

Apart from estimating the size of the burst, the ABT model designs a mechanism for multiple transmitting nodes to co-exist in an efficient manner. The idea is to let the contending nodes (secondary transmitters) use the bad duration of the on-going burst transmission (primary transmitter). The ABT model offers a MAC layer solution by sharing the link quality information with the neighbouring nodes. The primary transmitter embeds its burst size in data packets and the secondary transmitters overhear this information, thereby adjusting their duty-cycles accordingly. This in turn saves energy consumption. Furthermore, contending and relay nodes also benefit from this information. They can transmit their packets during the primary trasnmitter's halt period and vacate the channel as soon as the primary sender becomes active again.

This ABT protocol is implemented together with two state-of-the-art schemes in TinyOS platform and on TelosB sensor nodes for performance comparison. The experiments are divided into two categories. In the first category, the efficiency of the transmission scheme is compared in the presence of interference and mobility. The packet transmission rate improves up to 4% in the case of microwave interference and up to 34% in the presence of WiFi interference, as compared to other schemes. Also, the ABT protocol improves the packet success rate up to 36% when the transmitting node is mobile. These results signify the importance of adaptive and efficient link estimation strategies.

In the second set of experiments, the advantage of sharing link quality information on channel utilization is compared with the Baseline approach in a multi-hop network. The channel utilization is measured in terms of throughput and end-to-delay. Each ABT sender along the path shares the link quality metrics with its neighbouring nodes. The neighbouring nodes take advantage of this shared information by transmitting their packets to the next hop during the pause period of the primary transmitter. These experiments show that the ABT protocol improves the throughput up to 40% and reduces the end-to-end delay up to 52% on a multi-hop network. This implies that sharing link quality information can considerably improve channel utilization when transferring bulk-data transfer.

This dissertation addresses some important research queries concerning burst transmission: (a) Link quality fluctuations in static and mobile environments, (b) channel correlation, (c) determination of the correct size of the burst, (d) coexistence of multiple nodes during burst transmission, (e) end-to-end packet delay and energy consumption of the multi-hop network in a burst transmission. The dissertation proposes an efficient burst transmission scheme the design of which is based on the above research concerns. This protocol is implemented and integrated in TinyOS platform and on TelosB sensor nodes. Results show a considerable gain in throughput and decline in delay and energy consumption. This work demonstrates the benefit of employing efficient burst transmission schemes which model long-to-short term link quality fluctuations in wireless sensor networks.

8.2 Thesis Contributions

The thesis proposes offline, online, and hybrid approaches to model link quality fluctuation in static and mobile wireless sensor networks. The experimental results verified the usefulness of the proposed schemes. In summary, it makes the following contributions:

- A large empirical study was performed which led to a good understanding of how a link quality fluctuates due to external factors such as the environment (indoor, outdoor), cross technology interference (CTI), and the mobility of a sender node.
- I designed and developed two offline approaches, the CPB and DMB schemes, to model link quality fluctuation by estimating the expected duration in which the quality of a specific link remains stable.

- I proposed and implemented a MAC layer solution ABT to estimate the link quality fluctuations of mobile nodes online as well as to enable the coexistence of multiple transmitters during bulk-data transfer.
- I designed and implemented a hybrid burst transmission scheme by modelling both short-term and long-term link quality fluctuation.
- All the approaches were implemented using the TinyOS platform and deployed on TelosB sensor nodes to compare their performances.

8.3 Future Work

The link quality estimation models presented in this dissertation are designed and implemented for low-power wireless sensor networks. There are several possibilities for future research.

Mobility Management: In mobile wireless sensor networks, a handover mechanism is employed to support the mobility of the communication nodes and provide uninterpreted and reliable communication. A handover mechanism is a process in which a mobile sensor node searches for and connects to a new relay node when the quality of link with the current node starts to deteriorate. The handover mechanism usually suffers from the ping-pong effect which increases the cost of the handover considerably [LP05, SCW+06, QW12]. The burst size calculated by approaches presented in this thesis can be used together with the handover mechanism to overcome this ping-pong effect. Mobility management protocols can employ the correct burst size to schedule the packet instead of initiating the handover mechanism once the quality of link starts to deteriorate.

Routing metric: Routing protocols in wireless sensor networks such as the Collection Tree Protocol (CTP) uses link quality metrics such as the Expected Transmission Count (ETX), STLE, TALENT, and 4C, to predict the quality of the path between the sender and the receiver. The limitation of these transmission metrics is their inability to detect the period of good and bad duration in terms of the number of packets. Therefore, models proposed in this thesis can be used as a routing metric to predict the fate of 'n' number of packets, unlike those routing metrics mentioned earlier which are able to predict the fate of only a single packet.

Duty-cycling: Energy is a scarce resource in wireless sensor networks, as sensor nodes operate on battery power. Therefore, MAC protocols specify the duty-cycle for each sensor node to save energy. The duty-cycle of the sensor node is adjusted based on incoming data traffic. As discussed in chapter 6, the ABT protocol can improve energy consumption by adapting its sleep time based on the underlying link quality fluctuations. By integrating the ABT protocol with adaptive duty cycle protocols, performance can be improved and energy consumption can be reduced of the sensor node.

Ad-hoc network: The transmission schemes (CPB, DMB, H-DMB, and ABT) presented in this dissertation are designed to improve the energy consumption of wireless sensor networks in a highly dynamic environment. These models can also be employed in different wireless domain of IEEE 802.11, IEEE 802.22 and Narrow-band IoT (NB-IoT).

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